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Dallas Winter Visibility Study

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16. ABSTRACT

This report summarizes the findings of a Dallas field study during the December 1986 - March 1987 period. The objectives of the study were to identify the nature of winter visibility problems in Dallas, the constituents responsible for visibility degradation, and the sources of those visibility-reducing species. For the study period, the report concludes that coal/lignite combustion, vehicle operation, and wood combustion are the most important sources of the winter visibility problems. Proportions of the visibility degradation due to each source type are stated.

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THE DALLAS WINTER VISIBILITY STUDY

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SUMMARY

In the summer of 1986 the Region VI office of the EPA sought the assistance of Sandia National Laboratories in planning and carrying out a study of winter visibility impairment in Dallas. For some years, a highly visible cloud of polluted air could be seen over the city during winter season stagnation conditions. A historical study of visual range data collected from local airports conducted by the Texas Air Control Board (Zimmermann, 1985) showed a decreasing trend in the number of "good visibility" days per year over the past 35 years and, that the average visibility has decreased by 50 percent since 1960 (Figure S-1). Specific data describing the haze composition or source contributions to the winter pollution haze were limited. The purpose of this study, conducted jointly by Sandia National Laboratories and the Texas Air Control Board, with the assistance of the City of Dallas, was to determine the composition of the visible haze, and from that information, determine the relative contribution of the various air pollution sources in the Dallas area to winter visibility impairment.

Two existing air quality monitoring stations were augmented with additional instrumentation for this study. An urban sampling site selected for this study was Continuous Air Monitoring Station (CAMS) Number 5, operated by the Texas Air Control Board and located in North Dallas, several blocks south of the LBJ Freeway (I-635). A second site known as Bonnie View, operated by the City of Dallas, was located in a rural setting approximately 10 miles south of downtown Dallas. Continuous concentration data were collected for all regulated pollutants at the CAMS 5 site. Additionally, nephelometers (which measure light scattering by particles, an important contributor to visibility impairment) were operated at both sites. Dichotomous samplers which collect size-segregated aerosol samples were operated at both sites on a 12-hour schedule, beginning at 7 A.M. and 7 P.M. Aerosols consist of very small

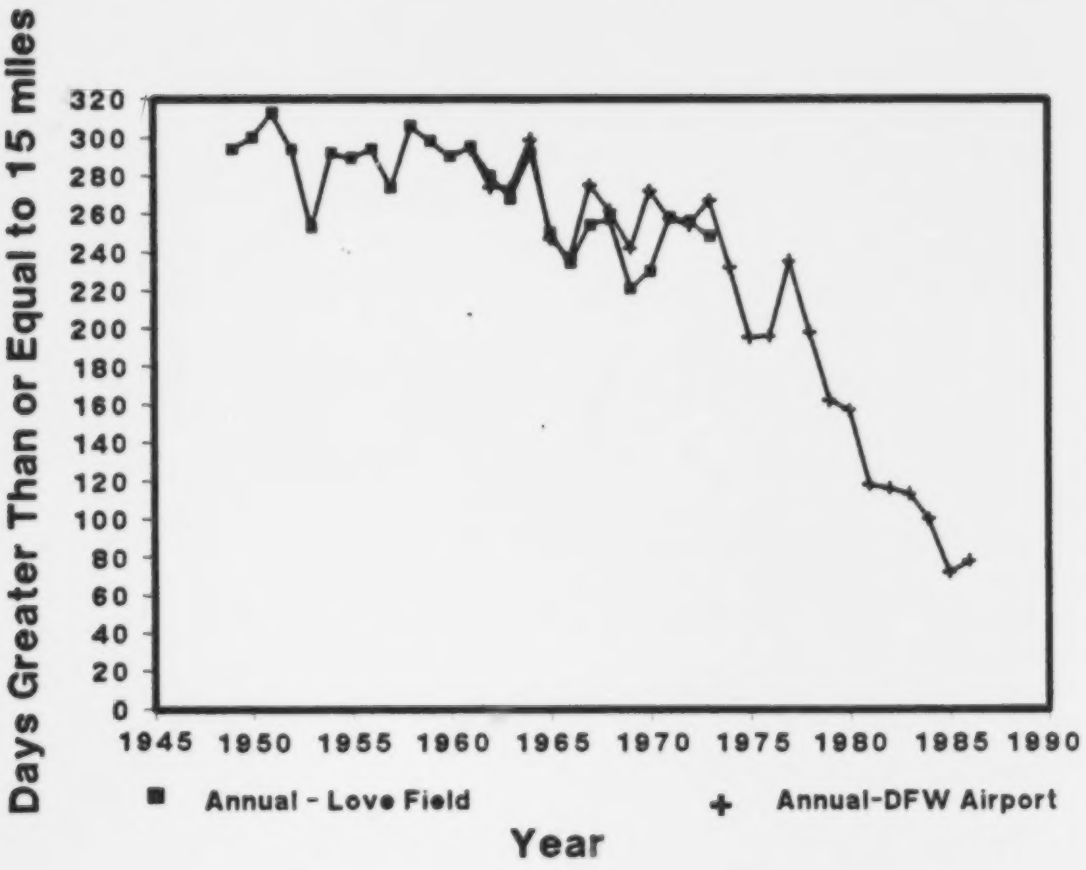

Figure S-1. Graphical summary of Dallas "good visibility" days (visibility greater than 15 miles) as recorded by human observers at local airports over the past 35 years. (from Zimmermann, 1985)

particles of dust, smoke, and other material suspended in the air. Previous visibility studies in other urban areas have shown that aerosols are the major cause of visibility impairment.

Aerosol sampling for this study was begun at both sites on December 15, 1986 and was continued on a daily schedule until March 3, 1987. On most weekdays, the continuous monitors showed peaks in the concentration of pollutants known to be associated with vehicles during traffic commute periods. Light scattering as measured by the nephelometers also peaked during the same rush hour periods. Additional peaks in the measured light scattering concentrations observed on selected evenings were associated with residential wood combustion.

Visibility impairment as indicated by light scattering measurements at the CAMS 5 site was judged, in comparison with similar measurements in other major urban areas, to be of light to moderate intensity during the study period. The observed pollution intensity was at least partially caused by an unusually wet and windy winter season which served to reduce the accumulation of pollutants for extended periods of time. During December and February the number of precipitation days was two times the expected and the three month total for precipitation days for December 1986 through February 1987 was 61 percent above the 30 year normal.

At both sites, aerosol mass concentration was measured in two size ranges: 0-2.5 and 2.5-10 micrometer aerodynamic particle diameter. One micrometer is one millionth of a meter. A human hair has an approximate diameter of 100 micrometers. The aerosol deposited on each filter was also analyzed for its elemental content. A comparison of the elemental content of aerosols collected from the air with the elemental content of the emissions from known pollution sources allows inferences to be drawn concerning the degree of contribution of each source type to the total collected aerosol and to the measured visibility reduction.

Selected samples collected at both the CAMS 5 site and the Bonnie View site were analyzed for both volatile and elemental carbon species. Elemental carbon, also known as graphitic carbon, is the black component in soot and is the major component of the ambient aerosol responsible for light absorption, an important physical process contributing to visibility reduction.

As studies in other cities have shown, light scattering as measured by the nephelometers was found to be highly correlated with the fine (0-2.5 micrometer) aerosol mass concentration, and not well correlated with the coarse (2.5-10 micrometer) particle size range. It is the fine particle size range that most efficiently scatters and absorbs light and as a result is largely responsible for visibility impairment. The fine particles were found to consist primarily of volatile carbon and sulfur compounds. Soil-derived elements were found to be a minor fraction of the fine particles and a major fraction of the coarse particles. A more detailed breakdown of the chemical composition of the fine particles is given in Figure S-2. The fine particles suspended in the air during this winter study consist largely of organic carbon (37% by weight contribution) and ammonium sulfate (26%) as determined for the day and night combined data set from CAMS 5. Minor species include elemental carbon (5%) and soil-derived elements (5%). Although particulate nitrate species were not measured in this study, they are estimated, on the basis of observations made in other urban areas, to be a significant component of the fine particles.

Pollution severity in Dallas during this study, as indicated by fine particle mass concentrations, was slightly less than reported in similar winter season visibility studies in other Western US cities. The average daytime fine particle mass concentrations in Dallas during the period of this study was 12.6 ug/m^3 (micrograms of particles per cubic meter of sampled air) whereas average values reported for recent studies in Denver, Albuquerque and Portland were 19.0 ug/m^3 and 18.6 ug/m^3, and 24.0 ug/m^3, respectively.

Apportionments of measured visibility impairment to the major sources in the region were constructed by multiple least squares regression methods for both sites from the combined (day and night) data set. The results for the urban CAMS 5 monitoring site are given in Figure S-3. Study results show that for this sampling site, on average, 33 percent of the daytime visibility degradation was apportioned to sulfate aerosol, principally derived from coal combustion sources, with 23 percent attributable to vehicular sources including diesel-powered vehicles,

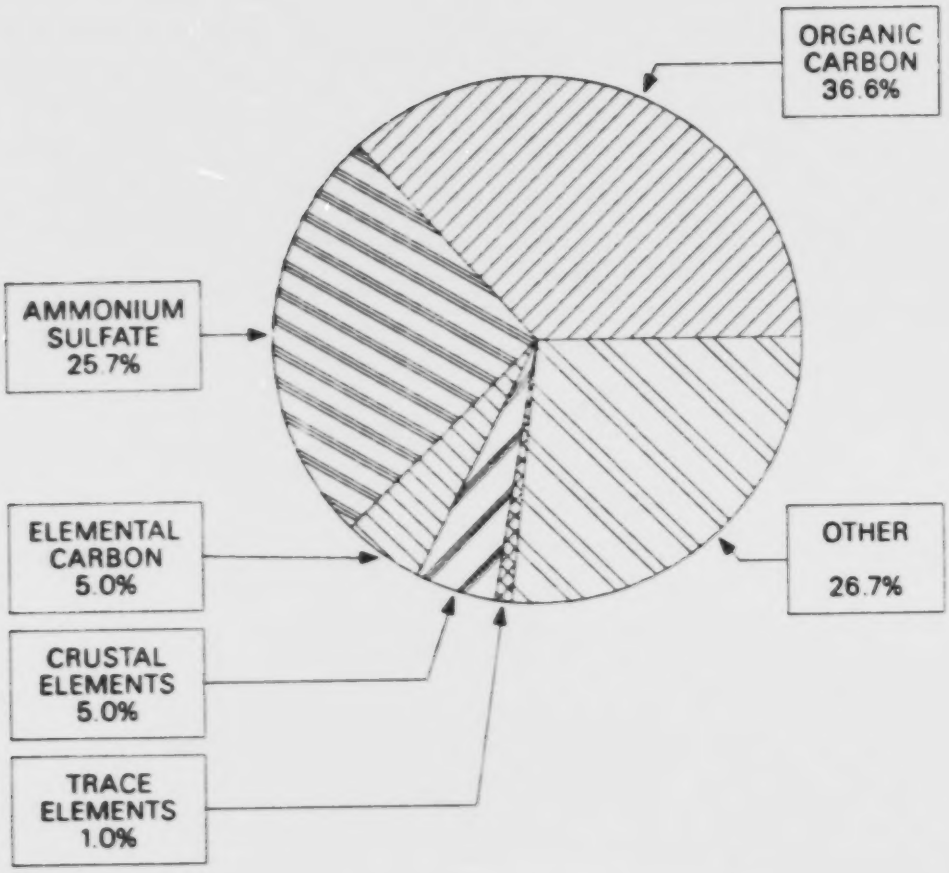

Figure S-2. Average chemical species composition of the fine particle aerosol collected at the North Dallas (CAMS 5) monitoring site.

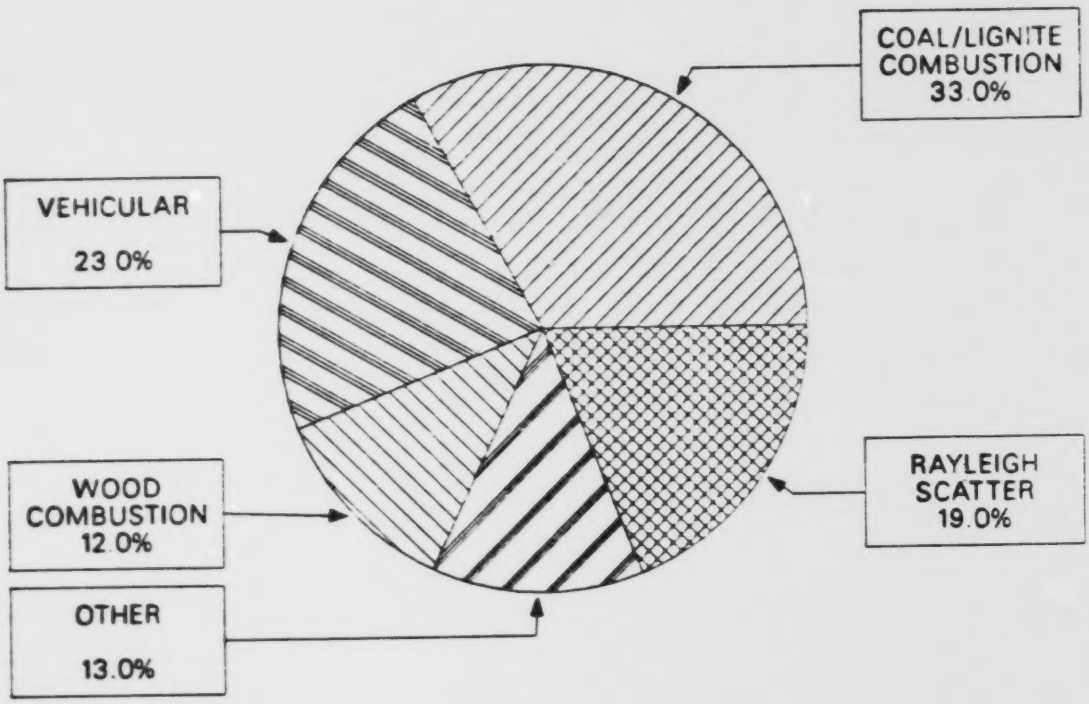

Figure S-3. Average source contribution to daytime visibility reduction as determined from combined daytime data collected at the North Dallas (CAMS 5) monitoring site.

and 12 percent from residential wood combustion sources. A small unapportioned category accounted for 13 percent of the total visibility reduction and is probably attributable to residential home heating and other unidentified sources. Approximately 19 percent of the average visibility reduction in the Dallas area is attributable to the naturally occurring process of light scattering by air molecules. A comparison of the apportioned visibility degradation for the urban site with a similar apportionment for the rural site reveals no major differences in the results, an observation which suggests that winter season pollution clouds have a relatively uniform composition over the Dallas area.

The study results show that sulfate aerosol, derived to a large extent from local and regional coal combustion sources, is a major contributor to visibility reduction in the Dallas area. Sulfate is a secondary aerosol pollutant formed in the atmosphere by the chemical conversion of sulfur dioxide gas emissions into particles that scatter light. Although it is difficult to determine precisely which sources are contributors to this sulfate category, an examination of emission inventories for the state of Texas provide important information in the assessment of this problem. A compilation of the tons of sulfur dioxide gas emitted by the major source categories on an annual basis shows that coal-fired power plants clearly top the list of sulfur dioxide emitters. Emissions from other industries employing coal-combustion processes such as local coal-fired cement processing plants may also contribute to the visibility reduction attributable to this coal combustion category. Vehicle exhaust emissions can also contain small amounts of sulfur dioxide from the trace amounts of sulfur in gasoline however this category would produce only a minor contribution relative to the large contribution from coal-fired combustion processes as noted earlier. The determination of contributions from other less important source contributions to sulfate aerosol including oil industry operations, fuel oil burning and natural sources was beyond the scope of this study. Industrial processes involving lignite combustion are also grouped in the coal combustion category in this study. Estimates

of the contribution of the coal combustion sources to visibility impairment as reported here are likely to be low since the light scattering data from this study are derived from measurements on a "dry" aerosol that is produced by heating the ambient air as it is drawn into the measuring instrument. Sulfate aerosols are known to interact with atmospheric water vapor in such a way that the light scattering efficiency of these "wet" particles is significantly enhanced. As a result of these considerations, the contribution of this coal combustion category to visibility impairment is likely greater than estimated by this study.

Examination of automatic camera photos of pollution clouds taken at two camera sites during this study allowed a classification of the daytime periods into categories determined by the color of the pollution cloud. On certain days a white, fog-like haze is observed and is caused by light scattering from high concentrations of sulfate aerosol. On other days a low level brown cloud can be observed. During the brown cloud periods, light absorption caused by elemental carbon (soot) is an important process contributing to visibility impairment. Elemental carbon is derived from vehicular and wood combustion sources.

Results from this study suggest that the dominance of one type of pollution cloud over another may be caused by meteorological conditions in the area. When wind speeds are low and air stagnation conditions are present, the pollution cloud is dominated by local vehicular and wood burning sources. When easterly or southeasterly winds persist for several days, high concentrations of sulfate aerosol may be transported into the region from distant coal combustion sources with a corresponding change in the physical appearance of the local pollution cloud.

The vehicular source is an important contributor to visibility reduction and includes those emissions from both catalyst and non-catalyst equipped gasoline-powered vehicles as well as all light and heavy duty diesel-powered vehicles. Heavy-duty diesel trucks and buses contribute a disproportionately large amount to visibility impairment. Per vehicle

mile traveled such vehicles exhaust, on average, more than 25 times the weight of fine particle emissions that catalyst-equipped vehicles emit. Furthermore, the high concentrations of elemental carbon particles in diesel exhaust as compared to gasoline engine exhaust are significant as a result of their light absorption properties. Calculations carried out, using data for total vehicles miles traveled in the area by vehicle type and data for the composition of exhaust from these vehicle types, show that about 60 - 80 percent of the total visibility impairment that is apportioned to vehicular sources is attributable to the diesel category.

Contribution of the residential wood combustion sources to daytime visibility degradation as determined by this study is light to moderate. The wood combustion source contributions are highest in the nighttime when, under conditions of clear skies and low winds, ground-based temperature inversions serve to trap pollutants near the ground in a concentrated layer.

To further characterize winter season pollution episodes in the Dallas area, additional data analysis and further experimental work should include the following:

Back trajectory models should be applied to the existing data set in an effort to yield additional information on the sources of the sulfate aerosol measured in the area. Results from trajectory analysis during periods of observed "white" clouds could provide important information on the location of distant coal combustion sources contributing to visibility reduction in the Dallas area. Satellite imagery for these periods of interest may also yield important clues concerning the origins of these aerosols transported from distant sources.

The routine use of a nephelometer should be implemented at a Dallas urban site in order to track visibility impairment on a seasonal and yearly basis.

The same visibility apportionment techniques used in this study should be applied to a similar data set collected in the summer season. This would allow one to effectively test the visibility apportionment results in the absence of residential wood combustion sources.

Additional measurements to determine the chemical composition of emissions from major local and regional sources would allow the application of Chemical Mass Balance models to derive an independent estimate of relative source contributions to winter season pollution.

Aerosol sampling east of the region of lignite and coal-fired power plants located in eastern Texas should be carried out in order to further explore the occurrence of long range transport of sulfate aerosol from coal-fired power plants from the eastern United States.

Gaseous and aerosol nitrate species should be measured in future sampling efforts using existing denuder measurement techniques. Information on nitrate species concentrations would provide a more comprehensive visibility apportionment result.

A series of measurements with nephelometers set up to measure both "dry" and "wet" aerosol should be made during the winter and perhaps other seasons. Although the operation of a nephelometer at ambient temperature is more labor intensive, the results would provide important information concerning the increased light scattering properties associated with "wet" sulfate aerosol and thus a more accurate picture of visibility impairment in the Dallas region.

A telephotometer and target system should be employed in future studies that would provide direct measurements of total extinction. This data, when coupled with heated and ambient nephelometer measurements, would provide important information on the scattering efficiency of sulfate aerosol under ambient humidity conditions.

Chapter I Introduction

The Dallas urban area, like many other U.S. urban areas, has experienced a decline in visibility over the past several decades. A quantitative estimate of this visibility degradation trend is available from an examination of daily airport visual range observations routinely conducted by National Weather Service personnel at Dallas Love Field and Dallas Fort Worth International Airport. A compilation of noon observations of visual range from both airport sites from 1948 to the present shows a decreasing trend in the number of days in a given year when the visual range is greater than 25 kilometers (Zimmermann, 1985) (Figure 1). Dallas residents are certainly aware of this visibility degradation since for some years a highly visible "brown cloud" has been observed in the Dallas urban area particularly during winter morning periods. Specific information on the composition of these winter stagnation pollution clouds prior to this study reported is unavailable. Although an extensive air monitoring network has existed throughout the Dallas area for many years, pollution monitoring equipment at these air sampling stations is primarily used for monitoring regulated pollutants such as ozone, oxides of nitrogen, carbon monoxide and total suspended particulate matter and, as a result, data from these sampling sites are not directly applicable to an understanding of the character and composition of these winter pollution episodes.

In an effort to gain important information on the composition and sources contributing to these pollutant clouds, the Region VI office of the Environmental Protection Agency initiated a study to look specifically at pollution episodes during the winter season and their impact on visibility degradation. Sandia National Laboratories was selected as a consultant for the project as a result of important

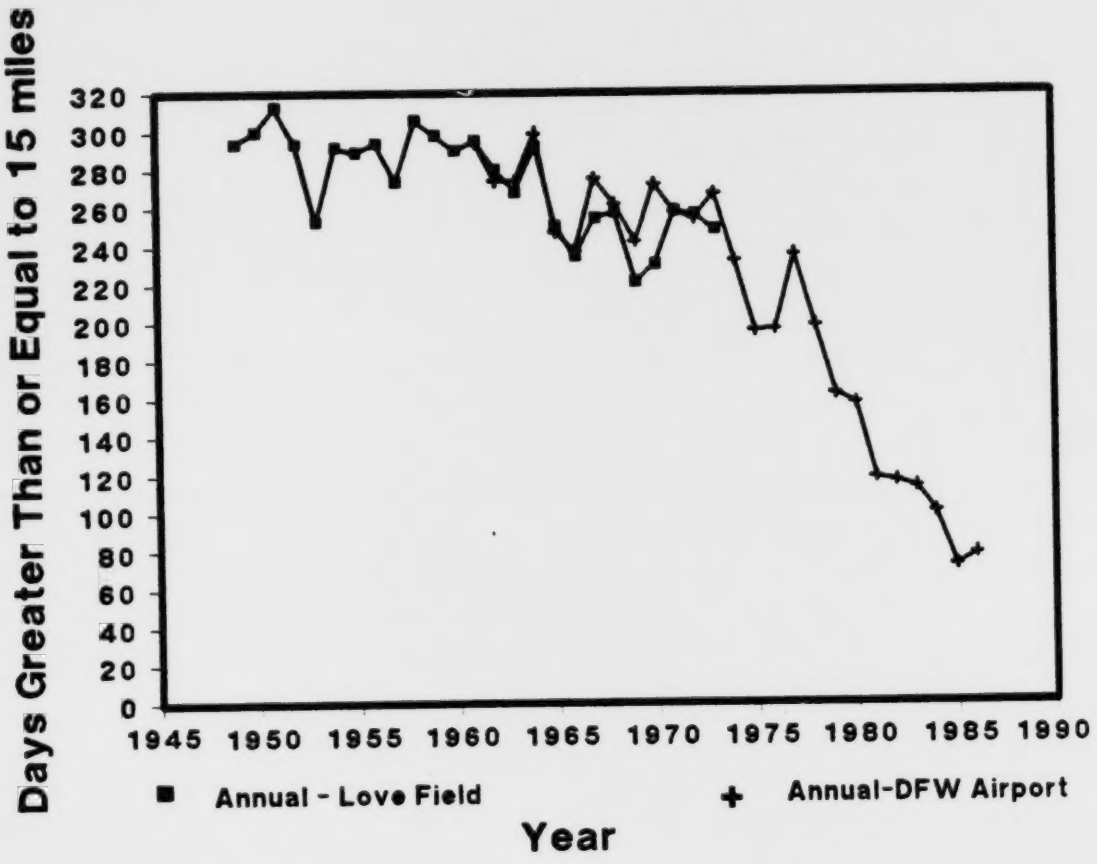

Figure 1. Graphical summary of Dallas "good visibility" days (visibility greater than 15 miles) as recorded by human observers at local airports over the past 35 years. (from Zimmermann, 1985)

experience gained during a similar winter visibility study that was carried out in Albuquerque, New Mexico. The Texas Air Control Board (TACB), a state agency with responsibilities in the area of air pollution monitoring and control, also had an interest in participating in a study that would provide information related to visibility degradation in Dallas and contributed in all phases of this study. TACB and City of Dallas air monitoring stations were supplemented with additional monitoring instruments for a first examination of the winter season pollution clouds and their related impacts on visibility.

This study is a receptor modeling study and as such one of its primary objectives is to determine the contributions of various pollution sources in the Dallas region to observed visibility degradation. Collection and analysis of the elemental content of aerosols at a receptor site coupled with knowledge about the elemental composition of the pollution sources encountered in the area through the application of statistical regression models allows one to quantify the contribution of various sources to the total visibility impairment. Results from this study can be used as an important source of information in future winter visibility degradation control strategies that may be implemented in the Dallas region. Similar receptor modeling analysis techniques have been applied in studies conducted in a number of cities including Denver (Groblicki et al, 1981; Lewis et al, 1986), Albuquerque (Zak et al, 1984), Detroit (Wolff et al, 1983), Los Angeles (Appel et al, 1983), Portland (Cooper and Watson, 1979), and Houston (Dzubay et al, 1982).

Chapter II. Visibility Theory and Air Pollution Fundamentals

Visibility degradation is one of the most noticeable effects of air pollution. It is characterized by both the apparent loss of clarity of distant objects and by an overall reduction in visual range. An urban pollution cloud often appears brownish in color and obscures the visual clarity of the landscape at a distance.

Visibility degradation is caused by the scattering and absorption of light in the air between the observer and the object observed. The degree of light loss, or extinction, at a given wavelength per unit distance along a sight line is given by the extinction coefficient, b_{ext}, which is defined by the Beer-Lambert law (Middleton, 1952):

$$I = I_o \exp(-b_{ext} x) \qquad (1)$$

where I_o is the original light intensity and I is the light intensity after passing through a column of air of length x. The extinction coefficient is given by the sum of various contributing components:

$$b_{ext} = b_{sg} + b_{ag} + b_{sp} + b_{ap} \qquad (2)$$

where b_{sg} represents the scattering of light by air molecules themselves (Rayleigh Scattering), b_{ag}, light absorption by gases (in urban air, predominately nitrogen dioxide), b_{sp}, light scattering by particles in the air, and b_{ap}, the absorption of light by particles. The total extinction coefficient can be determined by calculating or measuring each term on the right hand side of the equation and summing all terms. The molecular or Rayleigh scattering term is a known quantity and is linearly related to the ambient air density. Molecular absorption by the light-absorbing gaseous species nitrogen dioxide can be calculated from measured ambient concentration levels of nitrogen dioxide. Light

scattering by fine particles (b_{sp}) can be measured directly with an integrating nephelometer (Alquist and Charlson, 1967), and particle light absorption (b_{ap}) measurements are possible by light transmission measurements on aerosol samples collected on filters using the "integrating plate" measurement method described by Lin, (1973). It is also possible to measure b_{ext} directly with a telephotometer (Malm, 1979).

The extinction coefficient, b_{ext}, does not directly give a measure of visual range, which is formally defined as the distance at which an ideal black target can be visually differentiated by the average person against a horizon background. Assuming that an average person can discern a 2 percent difference in contrast between two objects, it is possible to derive the commonly-used Koschmieder visibility formula (Koschmieder, 1924):

$$V = 3.9 / b_{ext} \qquad (3)$$

where V is the visual range (meters) and b_{ext} is the total extinction (Mm^{-1}). Studies correlating b_{sp} (which normally constitutes a large portion of b_{ext} for an urban aerosol) and visual range have shown reasonably good agreement with this expression (Horvath, 1981).

Aerosol particle size distributions are of interest in visibility studies because, in general, the optical effects resulting from the interaction of electromagnetic radiation with a particle are strongly influenced by the size of the particle relative to the wavelength of radiation interacting with the particle. Urban aerosols typically exhibit a bimodal mass distribution with an intermodal minimum at approximately 3 micrometer particle diameter when aerosol mass is plotted as a function of particle diameter. Measurements of particle size distributions with high resolution instruments have shown that urban aerosol frequently are composed of three separate particle size ranges (Whitby and Liu, 1973). The first of these is commonly referred

to as the nuclei mode and contains particles less than 0.1 micrometer diameter. The nuclei particle mode is primarily composed of condensed gaseous material and is considered a highly unstable particle population. These particles have a limited lifetime as they readily coagulate with each other to form larger particles.

A second aerosol component includes particles ranging in size from about 0.1 - 2 micrometer diameter and is commonly termed the accumulation mode. Particles in this size range result from coagulation of particles in the nuclei mode, combustion processes, and gas-to-particle conversion processes occurring in the atmosphere. It is the accumulation mode size range that is most efficient at light scattering and resulting visibility degradation and is therefore of particular interest in visibility studies. Particles in the nuclei and accumulation size ranges have very low settling velocities (less than 0.02 cm/sec). As a result they remain suspended in the atmosphere for long periods of time. The first two aerosol components are collectively known as the fine particle fraction.

The third size category is known as the coarse particle fraction and comprises all particles larger than about 2 micrometer diameter. Aerosol in this size range results almost exclusively from mechanical processes and subsequent entrainment of these particles by wind, vehicular traffic, and other activities. Major sources of coarse particles include wind or mechanically entrained soil material or sea salt particles in the coastal regions of the country. Since the gravitational settling rate of a particle increases as the square of the diameter of the particle, the coarse particle fraction is short-lived as a result of higher settling rates as compared to the fine particle size fraction.

Aerosol sampling techniques that allow the separate collection of fine and coarse particle fractions simultaneously are possible with the dichotomous sampler (Dzubay et al, 1977). This air sampling instrument permits a separate determination of the chemical composition

of each particle size fraction. Knowledge of the chemical composition can provide important insight into the sources contributing to the collected aerosol. Important visibility reducing species normally encountered in ambient urban air include sulfates (ammonium sulfate, sulfuric acid, etc), nitrates, and water associated with these aerosol species. Important sources of these aerosols include coal-fired electric generating facilities, industrial processes using coal as an energy source and, to a limited extent, vehicular sources.

Aerosol carbon is another major constituent of urban aerosol and contributes significantly to visibility degradation. Aerosol carbon can be further divided into two components, namely, elemental carbon (C_{el}) and volatile carbon (C_{vol}). Elemental carbon in both urban and rural environments is produced from combustion processes such as diesel engine emissions. Volatile carbon is distinguished from elemental carbon in that hydrogen, oxygen and other elements are chemically bound to the carbon. Volatile carbon can be directly produced by combustion sources or formed by secondary reactions of gaseous organic compounds in the atmosphere. Elemental carbon is of particular interest in visibility studies because it contributes to light extinction through both absorption and scattering processes. Consequently, the contribution of elemental carbon to light extinction is much greater per unit mass than of other non-absorbing aerosols.

Chapter III. Measurements

A. Sampling and Camera Site Descriptions

Two existing sampling sites in the Dallas area were augmented with additional instrumentation for this study. The primary site was a Continuous Air Monitoring Station (CAMS) known as CAMS 5 operated by Texas Air Control Board personnel. This site is located in North Dallas, approximately 10 miles from downtown Dallas and several blocks south of the LBJ freeway (I-635) as shown in Figure 2. This sampling station is situated on the perimeter of a grass-covered school playground in a residential neighborhood. Extensive commercial development including shopping malls and office buildings are found several blocks to the north along the LBJ freeway. The site elevation at CAMS 5 is 192 m mean sea level (MSL). All roads in the immediate area are paved. Dichotomous samplers were deployed on the roof of an instrument shelter which housed all the continuous monitors used in the study.

A second site known as Bonnie View is located approximately 12 miles south-southeast of the Dallas downtown area near the intersection of the I-635 and I-45 freeways as shown in Figure 2. Elevation at this sampling site is 177 m MSL. The site is adjacent to a rural paved road and surrounded by farm land. No commercial development centers are found within a 3 mile radius of the site. Dichotomous samplers were positioned on the roof of an instrument shelter that housed all the continuous monitors used at this location.

Automatic 35 mm cameras were employed at two locations where photographs were taken at 9 A.M., 12 noon and 3 P.M. The first camera was located at Cedar Valley College, less than 1 mile from the Bonnie View site, and had a view of the Dallas downtown complex approximately 11 miles to the north. Elevation at this site was 183 m MSL. A second camera was positioned at Dallas Love Field, a municipal

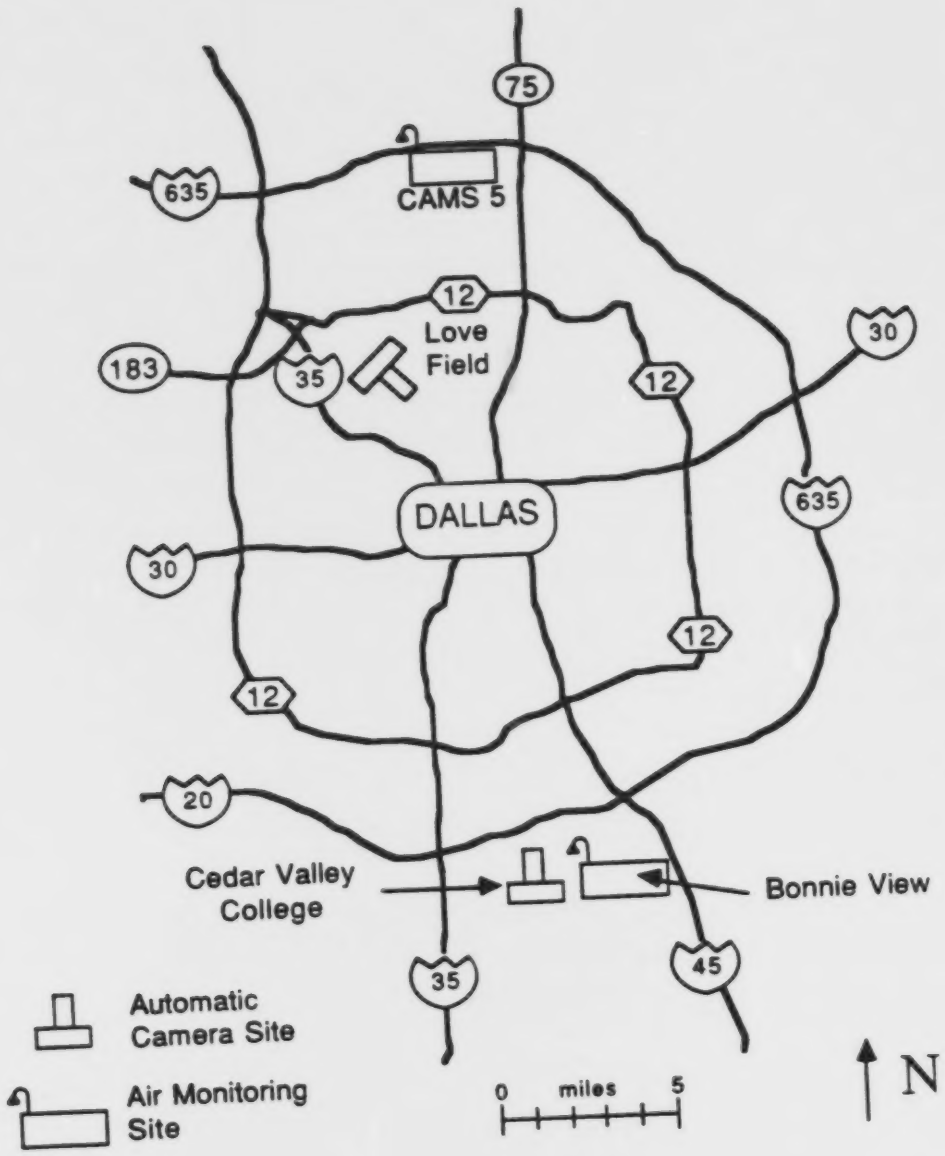

Figure 2. Map of the Dallas area showing the main CAMS 5 site, the background Bonnie View site and the two automatic camera sites.

airport, where an unobstructed view of the downtown complex, 5 miles to the southeast, was available. Elevation at this site was 152 m MSL.

B. Aerosol Sampling

Aerosol sampling instrumentation employed at the CAMS 5 and the Bonnie View sites was as follows: At each site four dichotomous samplers (Andersen Model 244E) were set to run on a 12-hour (0700 - 1900 and 1900 - 0700) schedule. Two samplers were operated during each 12-hour sampling period. One sampler was equipped with 2 micrometer pore size Teflon filters (Andersen Part No C-240-PR-T2) and the other was equipped with pre-fired quartz filters (Pallflex/Type 2500 QAST) such that simultaneous fine (0-2.5 micrometer aerodynamic diameter) and coarse (2.5-10 micrometer) aerosol samples were collected on both types of filter media. Sampler total and coarse flow rotameter readings were recorded by site personnel following installation of the filter on the sampler and immediately prior to removal of the filter from the sampler. To insure flow measurement accuracy, sampler flow rates were checked against laboratory calibrated mass flow sensors at several times during the study.

Both sites were equipped with photon-counting integrating nephelometers (MRI Model 1597) operated in a "heated" mode. Calibration of these instruments was carried out at the onset and periodically throughout the study using Freon-12 span values as published by Ruby and Waggoner (1981). The Rayleigh scatter component was zeroed out on the nephelometers such that only aerosol light scattering was measured by the instrument. Zero and electronic span checks were performed on these instruments daily.

C. Gas Measurements

Gas instruments at the CAMS 5 site included an ultraviolet absorption ozone monitor (Dasibi Model 1003AH), a pulsed fluorescence sulfur dioxide monitor (Thermo Electron Model 42), a chemiluminescent oxides of nitrogen monitor (Thermo Electron Model 14B/E) and a gas filter correlation carbon monoxide monitor (Thermo Electron Model 48). Data integrity from the continuous gas monitors at the CAMS 5 site was monitored three times per week with automatic zero and span calibration checks. Weekly automatic multi-point calibration checks were also employed during the study. A complete list of all instruments deployed at both sampling sites is given in Table 1. Other instrumentation employed at the CAMS 5 site included a chilled mirror hygrometer (EG&G Model 880) for measurement of dew point as well as wind speed, wind direction and temperature sensors positioned on a tower 10 meters above ground.

Data acquisition from all instruments at the CAMS 5 site was accomplished via a telephone link of an on-site data logger to a central computer at TACB central offices in Austin. An additional data logger was linked by telephone to a data processing computer at Sandia National Laboratories in order to permit periodic examination of the continuous monitor data.

Gas instruments at the Bonnie View site included a chemiluminescent oxides of nitrogen monitor (Bendix Model 8101C), a non-dispersive infra-red carbon monoxide instrument (Bendix Model 8501-5CA) and a chemiluminescent ozone analyzer (Bendix Model 8002). Zero and single point span checks were automatically performed via remote computer control on all gas monitors on a daily basis.

Data aquisition was accomplished at the Bonnie View site by two data loggers, one telephone-linked to a City of Dallas central computer and the other telephone-linked to data processing facilities at both Sandia National Laboratories in Albuquerque, and Texas Air Control Board headquarters in Austin.

Table 1. Aerosol and gas monitoring instruments used at the CAMS 5 and Bonnieview sampling sites.

Parameter	Instrument
Aerosol mass	Dichotomous sampler, Teflon filter
Aerosol elemental composition	Dichotomous sampler, Teflon filter
Carbon aerosol	Dichotomous sampler, Quartz filter
Light scattering coefficient	Integrating nephelometer
Ozone	UV absorption analyzer[1] Chemiluminescent analyzer[2]
Nitrogen oxides	Chemiluminescent analyzer
Carbon monoxide	Gas filter correlation analyzer[1] Non-dispersive infra-red analyzer[2]
Sulfur dioxide	Pulsed UV fluorescence analyzer[3]

[1]CAMS 5 site

[2]Bonnieview site

[3]CAMS 5 site only

D. Automatic Camera System

The camera systems used in this study consisted of 35 mm cameras (Olympus OM2) with automatic winders and data backs for recording the date on each photographic slide. Lenses used were 135 mm fixed focal length with ultraviolet filters. Three digital clocks triggered the camera's shutter at 9 A.M., 12 noon and 3 P.M. each day. The camera's shutter speed was automatically chosen by the camera to produce a consistent exposure with the camera's lens aperature set at f4.0. The camera, timer, and associated batteries were housed within a sealed weather-tight enclosure. The camera was positioned behind a high quality clear plexiglas window in the front of the enclosure. A low speed transparency film (Kodachrome 25) was used for all photographs taken during this study. This film provides an optimum color rendition and is relatively stable before and after film processing. A color chart and a gray scale chart was photographed at the beginning and end of each roll of film to document the color characteristics of that particular roll. All film processing was done by Kodak laboratories.

E. Soil Sampling

Soil samples were collected during the study at both sites by scraping topsoil and road dust from the immediate vicinity of each site. These samples were then mixed, dried, sieved and aerosolized using a fluidized bed aerosol generator (TSI Model 3400). The re-suspended aerosol was then sampled using a dichotomous sampler of the same design as employed at the sampling sites. The samples were collected on pre-weighed Teflon filters and weighed on an electrobalance (Cahn, Model 29) following sampling to determine the total soil mass deposited on the filters. The filters containing the fine particle soil deposits were then analyzed by X-ray fluorescence to determine the elemental content of the soil material.

F. Analytical Techniques

Analysis performed on the dichotomous sampler Teflon filters included the aerosol mass collected on the dichotomous sampler filters by gravimetric methods. An electrobalance (Cahn Model 27) was used in a controlled temperature and humidity environment to weigh all Teflon filters before and after installation and sampling on the dichotomous sampler. Weighing precision as determined by repeated weighings of a constant mass was determined to be ±20 micrograms (TACB, 1986). Elemental analysis was accomplished using an energy dispersive X-ray fluorescence (XRF) spectrometer at the Lawrence Berkeley Laboratory using techniques described by Goulding et al (1978).

Carbon analysis of aerosol deposited on the quartz filters was carried out at Sunset Laboratories using a two-step thermal volatilization/combustion method in order to sequentially measure volatile carbon species (C_{vol}) and elemental carbon species (C_{el}). A detailed description of this technique is given by Johnson et al (1981).

IV. Data Processing and Quality Assurance Summary

A comprehensive quality assurance (QA) program was carried out during the sample collection and analysis portion of this study. Participating agencies and the QA techniques applied are given in Table 2 for the major parameters of interest in this study.

Examination of both XRF and carbon data revealed the presence of an aluminum sampling artifact on the coarse filters and to a lesser extent on selected fine filters. These particles were determined, upon further investigation, to originate from the vibration of a metal to metal contact between the dichotomous sampler inlet tube and the outlet tube of the 10 micrometer particle cutoff device. Fine and coarse particle filters that were inadvertently switched during filter changeout procedures were also noted during the review of these analysis data.

An independent measure of the general quality of both the XRF and aerosol carbon analysis results was confirmed by a high correlation (R^2=0.79) between coarse calcium as determined by XRF and coarse carbonate as determined by sequential combustion analysis. Precision errors of ±16% for these measurements are estimated based on this correlation result. The combined total accuracy (sampler flow rate and analysis uncertainty) is estimated to be ±25% or better for the XRF and aerosol carbon measurements.

Several checks of the final data sets for each sampling site were carried out to further insure data quality and identify possible data errors. Aerosol mass, as determined by gravimetric analysis, was compared to the sum of the elemental oxides and carbon compounds as determined by XRF and carbon analysis. The fine mass sum typically equalled about 67% of the gravimetric mass with a standard deviation of

Table 2. Data validation procedures and responsible agencies for gas and aerosol data collected during this study.

Agency	Parameter	Data Validation Technique
TACB Laboratory	Dichotomous sampler flow	Periodic checks with calibrated mass flow meters
	Aerosol sample integrity	Visual inspection of exposed filters
	Aerosol mass	Replicate and control weighing
TACB Region 8	NO_x, SO_2, CO, O_3 at CAMS 5	Daily span and zero checks
City of Dallas	NO_x, CO, O_3 at BV	Daily span and zero checks
Sunset Laboratory	Aerosol carbon species	Replicate filter analysis Control standards
Lawrence Berkeley Laboratory	Aerosol elemental composition	Replicate filter analysis Standard elements
TACB Research	Light scattering coefficient and Freon-12 span checks	Periodic dark current, zero
	Automatic camera Photographs	Standard color chart photographs and developing techniques
	Aerosol Mass Concentration	Examination of FPM/CPM ratios Mass balance calculations

12.5%. With the consideration that water of hydration, nitrates, and the oxygen of the organic compounds are not included in this total, the mass sums compare favorably with the measured mass. Samples that exhibited significant deviations from this weight fraction were further investigated for reliability. The coarse mass sum typically equalled about 51% with a standard deviation of 20%. These results are judged to be less informative since no coarse particle X-ray attenuation corrections were applied to the XRF data. High aluminum concentrations observed on the coarse filters were directly related to the sampler artifact problem noted above. In light of the above considerations, and the fact that coarse particles have been shown to contribute little to visibility degradation, the coarse particle data set was used only for qualitative information in this study.

Although the original QA plan specified the periodic operation of co-located dichotomous samplers in order to derive precision estimates for mass concentration data, the unexpected sampler artifact problem was particularly pronounced on one of the QA samplers and as a result caused a positive mass bias on this sampler. In light of the sampler artifact problems, this particular phase of the QA program was considered of limited utility and sampler performance validation was determined by the alternate QA program involving periodic sampler flow audits and gravimetric control procedures. These flow audits and gravimetric control procedures were a satisfactory alternative and did in fact fulfill the established quality assurance requirements. The reader is referred to the final QA Plan and QA Report for additional details and QA performance information (TACB, 1988).

V. Results and Discussion

A. Local Weather Summary

A comparison of observed weather parameters such as temperature, precipitation and cloud coverage as recorded at local National Weather Service facilities during this study was compared to thirty year average values in order to set the meteorological conditions encountered during this study in the context of an "average" winter season. The mean temperatures for the December 1986 through February 1987 were only slightly different from the 30 year averages. The three month average for the study period was only 0.4 degrees F above normal. Average minimum and maximum temperatures also compared favorably with the 30 year averages.

The number of precipitation days in Dallas was above average during December 1986 and February 1987. Figure 3 shows the measurable precipitation as recorded at DFW Airport for December, January and February as compared to the 30 year average. Measurable precipitation for the study period was 40 percent higher than the 30 year average for this winter period. During December and February, the number of precipitation days was twice what would be encountered on the average. The three month total for precipitation days for the entire study period was 61 percent above the 30 year norm. These observations are helpful in understanding the severity of the pollution season since precipitation is usually associated with such meteorological occurrences as frontal movements, increased vertical mixing and increased surface winds - conditions which serve to dilute existing pollution clouds and cause a natural improvement in visibility.

Cloud coverage, like extent of precipitation, can also be a factor in determining the potential for the formation of stable atmospheric conditions with associated ground-based inversions. During December and

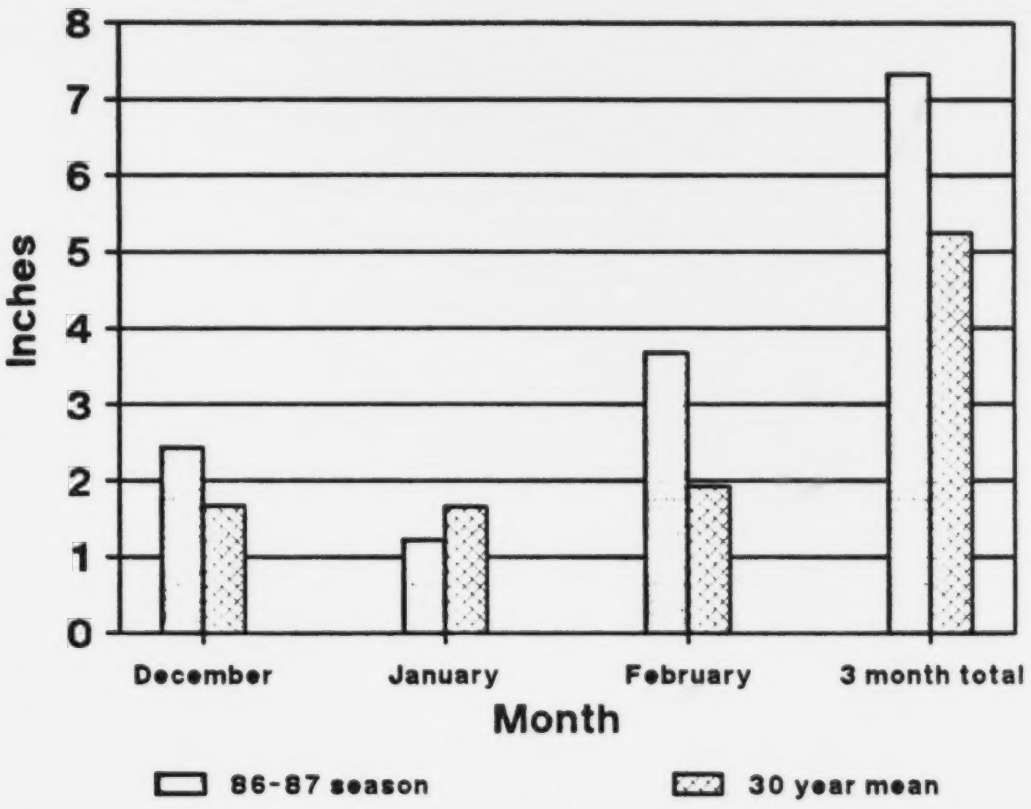

Figure 3. Recorded monthly precipitation for the study months of December, January and February as compared to the 30 year average for those months.

February, the number of days with reported cloud coverage was greater than average while January was slightly below average. The three month average cloud coverage for the study period was slightly over 10 percent greater than average.

Although many of the observed meteorological indicators suggest that this particular season was less severe in terms of visibility degradation than usual, no visibility data as measured by an integrating nephelometer are available from previous years to compare to the measurements that were made during this study.

B. Aerosol and Gas Concentrations

The study was conducted continuously through a 3 month period from December 15, 1986 through March 3, 1987, however, because of cost constraints, a subset of filters was selected for XRF analysis. Selection criteria were based primarily on fine fraction filters with the highest mass loadings which corresponded to those day and night periods when the measured scattering values were also high. Priority was given to the selection and analysis of fine fraction samples from both sites with a secondary emphasis on coarse samples. From the CAMS 5 site, 74 fine fraction filters and 46 coarse fraction filters were submitted for XRF analysis and from the Bonnie View site, 33 fine filters were analyzed. A total of 91 fine fraction quartz filters from both sampling sites was submitted to Sunset Laboratories for aerosol carbon analysis.

Overall average concentrations calculated from 12-hour concentrations for fine aerosol components, extinction components and gas concentrations for combined day and night sampling periods are given in Table 3 for the CAMS 5 and Bonnie View sampling sites. The average fine mass concentration at the CAMS 5 site was 16.0 $\mu g/m^3$ and is comparable to an average value of 17.7 $\mu g/m^3$ obtained at the Bonnie View site. The average light scattering coefficient was 48 Mm^{-1} at CAMS 5 as compared to a slightly higher average of 56 Mm^{-1} at the Bonnie View site.

Table 3. Fine fraction aerosol, gas and light scattering averages, uncertainties and maxima as measured at the CAMS 5 and Bonnie View sampling sites from December 15, 1986 through March 15, 1987.

SPECIES	CAMS 5			BONNIE VIEW		
	average	uncert	maximum	average	uncert	maximum
MASS (ng/m3)	16057	2407	60140	17671	2651	43970
C_{el} (ng/m3)	744	74	2230	634	63	2030
C_{vol} (ng/m3)	4283	428	32400	3462	346	10460
Al (ng/m3)	253	84	1630	525	159	2630
Si (ng/m3)	113	19	382	134	21	503
S (ng/m3)	998	39	5370	1245	50	6980
Cl (ng/m3)	21	5	145	19	5	56
K (ng/m3)	79	3	390	69	3	254
Ca (ng/m3)	61	2	161	78	3	246
Ti (ng/m3)	7	12	37	10	10	42
V (ng/m3)	4	8	19	5	8	15
Cr (ng/m3)	4	6	12	7	5	17
Mn (ng/m3)	4	4	11	4	4	11
Fe (ng/m3)	49	3	131	52	3	120
Cu (ng/m3)	6	1	26	6	1	17
Zn (ng/m3)	15	1	51	17	1	54
Br (ng/m3)	7	1	28	8	1	41
Pb (ng/m3)	26	2	72	30	2	121
Ba (ng/m3)	3	22	23	2	23	23
O_3 (ppb)	15.4	2	52.0	18.5	2	52
NO (ppb)	18.8	5	155.0	11.1	5	135
NO_2 (ppb)	14.3	5	49.0	14.7	5	53
NO_X (ppb)	33.1	5	196.0	24.7	5	188
SO_2 (ppb)	<2	2	8.0	N/A	N/A	N/A
CO (ppm)	0.7	0.05	2.2	0.5	0.2	2.8
b_{sp} (35°C) (Mm^{-1})	47.5	2	163.7	55.8	2	190.2

Elements with average concentrations less than 2 ng/m^3 not shown in the table include: Ni, Ga, Ge, As, Se, Rb, Zr, Mo, Ag, Cd, Sn, Sb, and I

These values are comparable to or lower than average values encountered in other urban visibility studies. For example, the average nephelometer value during a comparable winter study in Albuquerque was 130 Mm^{-1} (Zak et al, 1984). For a similar study in Denver, average day and night values of 55 and 77 Mm^{-1} were reported respectively (Lewis et al, 1986). Major differences between the CAMS 5 site and the Bonnie View site are not apparent as judged by a comparison of average mass and nephelometer measurements.

Comparable average values were also obtained for both volatile and elemental carbon at both sites with a slightly higher value of 5.0 $\mu g/m^3$ total carbon encountered at the CAMS 5 site as compared to 3.5 $\mu g/m^3$ at the Bonnie View site. Elements whose average concentrations were significantly above background at both sites included Al, Si, S, Cl, K, Ca, Fe, Zn, Br and Pb.

Gas concentrations as measured at both sites are characterized by measurable levels of NO, NO_2, NO_X, O_3 and CO with SO_2 levels typically at or below the 2 ppb limit of detection of the instrument used at the CAMS 5 site. As noted for the aerosol concentration averages, no major differences were encountered for the average gas values as measured at both monitoring sites. Hourly concentration data for all of the continuous monitors at the CAMS 5 site for a selected period of the study are given in Figure 4 to illustrate some of the trends apparent in the measurements. One of the highest nephelometer readings during the study was observed on the evening of December 24 and is accompanied by a low wind speed reading for the same period. On the following day, December 25, high values for CO, NO, NO_2 and NO_x were observed and were also accompanied by low wind speeds.

Similar averages grouped by day and night sampling periods for the CAMS 5 site are given in Table 4. Average concentrations for most elements are higher in the evening hours, an observation consistent with pollutant emissions into reduced atmospheric mixing depths caused by nightime temperature inversions.

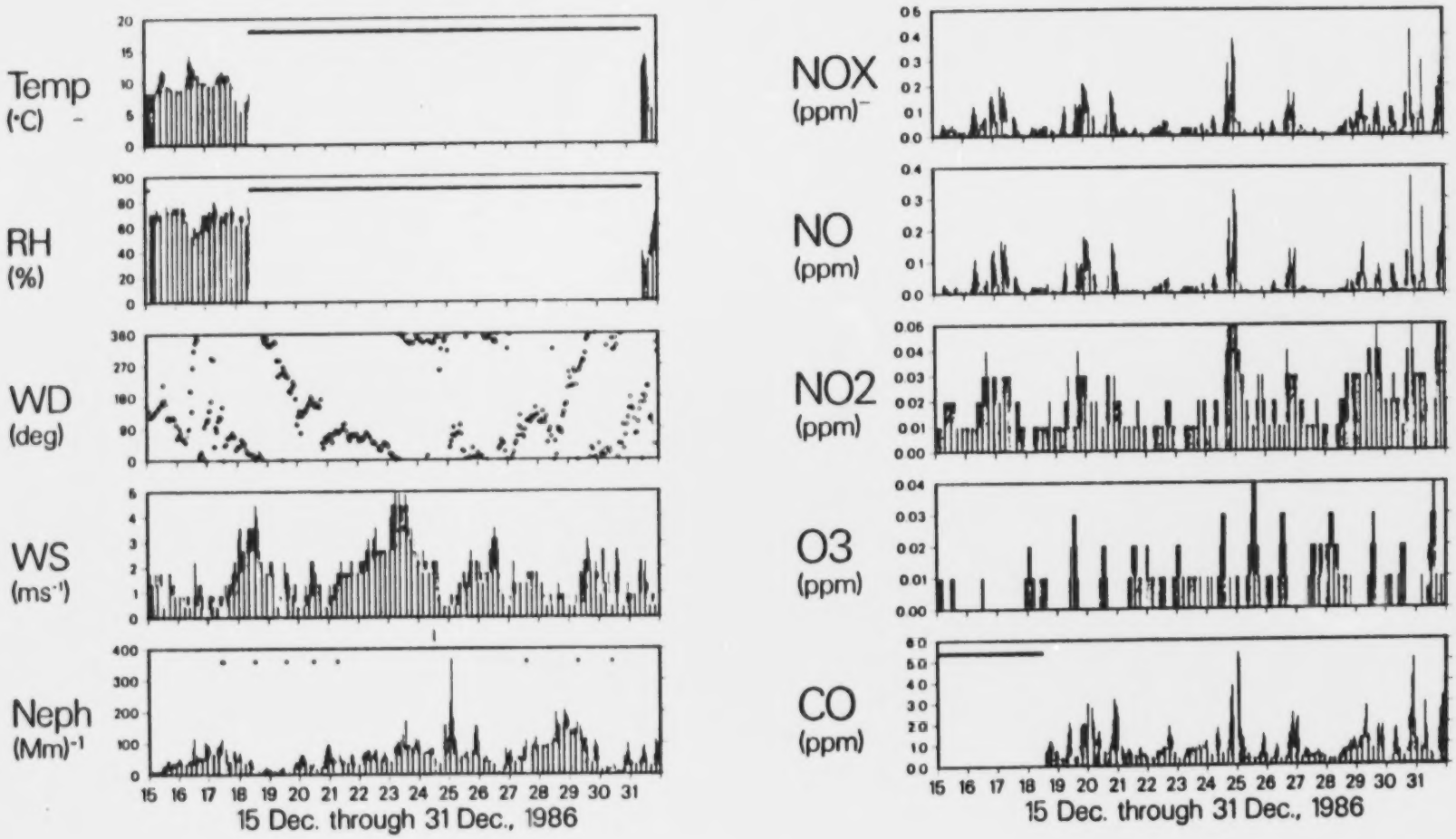

Figure 4. Real-time data from the CAMS 5 monitoring station for the period December 15 - December 31, 1986.

Table 4. Fine fraction aerosol, gas and light scattering averages from the CAMS 5 day (0700-1900) and night (1900-0700) sampling periods

SPECIES	DAY		NIGHT	
	average	maximum	average	maximum
MASS (ng/m3)	12579	36650	19441	60140
C_{el} (ng/m3)	765	1620	722	2230
C_{vol} (ng/m3)	2840	6610	5899	32400
Al (ng/m3)	115	414	388	1630
Si (ng/m3)	119	330	108	382
S (ng/m3)	1062	5370	936	3430
Cl (ng/m3)	8	27	35	145
K (ng/m3)	52	110	106	390
Ca (ng/m3)	66	157	56	161
Ti (ng/m3)	7	25	7	37
V (ng/m3)	3	16	5	19
Cr (ng/m3)	4	12	5	12
Mn (ng/m3)	4	11	3	9
Fe (ng/m3)	49	108	48	131
Cu (ng/m3)	4	9	8	26
Zn (ng/m3)	14	48	16	51
Br (ng/m3)	5	14	9	28
Pb (ng/m3)	21	55	31	72
Ba (ng/m3)	5	23	1	17
O_3 (ppb)	19.5	52.0	11.1	47.0
NO (ppb)	16.5	72.0	21.2	155.0
NO_2 (ppb)	12.6	33.0	15.9	49.0
NO_x (ppb)	29.0	97.0	37.2	196.0
SO_2 (ppb)	<2	6.0	<2	8.0
CO (ppm)	0.6	1.7	0.7	2.2
b_{sp} (35°C) (Mm^{-1})	46.0	136.0	49.0	163.7

Notes: Measurement uncertainties are given in Table 3.

Elements with average concentrations less than 2 ng/m^3 not shown in the table include: Ni, Ga, Ge, As, Se, Rb, Zr, Mo, Ag, Cd, Sn, Sb, and I

C. Chemical Composition of Fine Particle Mass

A characterization of the fine particle mass by chemical species is included in Table 5 for the day, night and combined sampling periods at the CAMS 5 monitoring site and graphically shown in Figure 5 for the combined data set. As a result of time constraints and the lack of availability of a suitable sampler, nitrate species were not measured during this study. Organic carbon is derived by multiplying the average volatile carbon values by a factor of 1.4 to account for associated oxygen and hydrogen according to Shah (1983). Ammonium sulfate concentrations are derived by assuming that all sulfur on the filters as determined by XRF analysis is in the form of ammonium sulfate. Other studies have shown that good correlation exists between elemental sulfur as determined by XRF and sulfate as determined by ion chromatographic techniques and that the ratio of sulfate to sulfur is very close to 3 as one would expect for the assumption to be valid. (Zak et al, 1984 and Stevens et al, 1986). Nitrate species are included in the "other" category which is the difference between the average fine particle mass concentrations and the sum of the species measured by XRF and carbon analysis. Organic carbon is the largest contributor to fine particle mass for day, night and combined sampling periods and is followed by ammonium sulfate and elemental carbon. The contribution from the crustal source was minor and was derived by multiplying the average silicon (Si) concentrations by the ratio of soil-derived FPM to Si as determined in the soil analysis experiments. The high levels of organic carbon are not surprising since this aersol component is common to both vehicular and wood combustion sources as well as natural gas fired home heating. The observed high levels of sulfate indicate the importance of secondary aerosols that are characteristically associated with coal combustion sources. An estimate of plume age based on the observed particulate to gaseous sulfur ratio and an assumed gas to particle reaction and

Table 5. Fine particle mass by chemical species for, day, night and combined sampling periods from the CAMS 5 monitoring site.

Species	Day ($\mu g/m^3$)	Night ($\mu g/m^3$)	Day + Night ($\mu g/m^3$)
Organic Carbon[1]	4.0	8.3	6.0
Ammonium Sulfate[2]	4.4	3.9	4.1
Elemental Carbon	0.8	0.7	0.7
Crustal Elements[3]	0.8	0.7	0.7
Trace Elements	<0.1	<0.1	<0.1
Other[4]	2.6	5.8	4.4

[1]Organic carbon = C_{vol} * 1.4 from Shah (1983).

[2]Calculated by assuming that all sulfur determined by XRF is ammonium sulfate

[3]Estimated by multiplying the Si concentrations as determined by XRF by a factor of 6.6 to account for all soil mass as described in the text.

[4]This category was determined by subtracting the sum of all measured species from the average FPM concentration. Nitrates, adsorbed water and other species are included in this category. See text for additional discussion concerning nitrate concentrations.

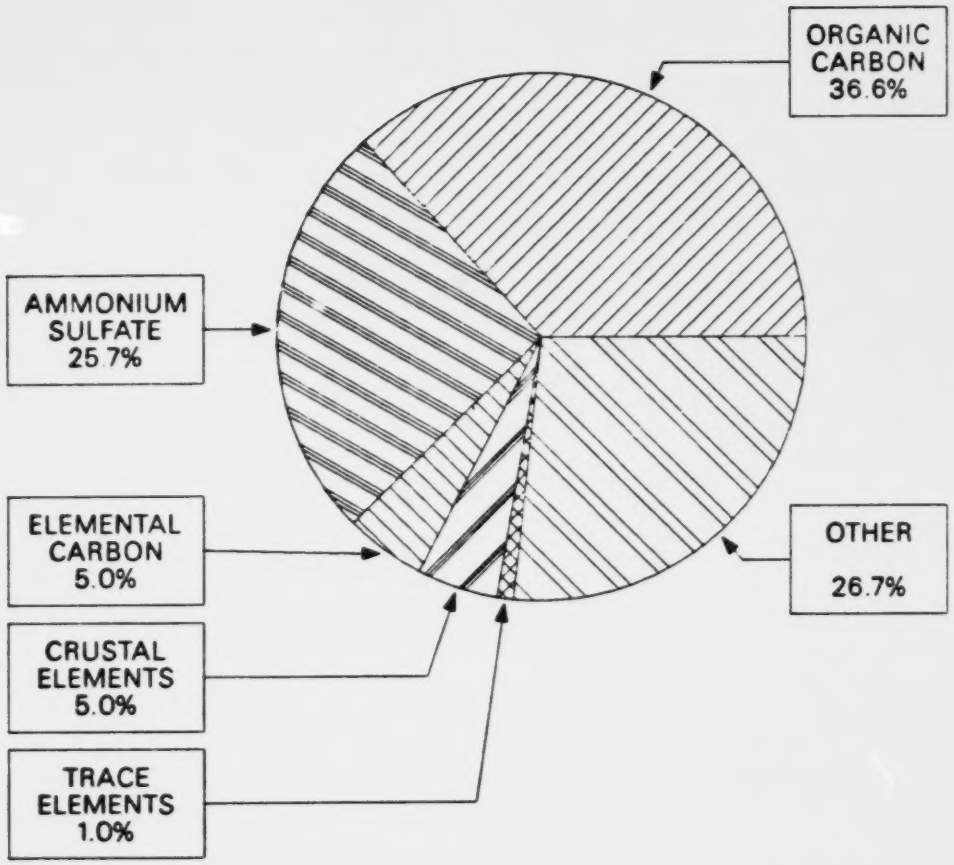

Figure 5. Average chemical species composition of the fine particle aerosol collected at the North Dallas (CAMS 5) monitoring site.

deposition rate of 0.003 h^{-1} and 0.007 h^{-1} respectively, was obtained by use of a hybrid receptor model described by Lewis et al (1985). For this data set an average plume age well in excess of 100 hours was obtained, a result that further suggests that long range transport of distant coal combustion emissions may play an important role in determining Dallas air quality. The low SO_2 levels observed during the study further suggests that local coal combustion sources are not significant contributors to this observed sulfate, since local emissions would likely contribute both SO_2 and sulfate.

D. Extinction Budget

A summary of observed extinction, classified by physical type, is given for the day, night and combined subsets for data taken at CAMS 5 in Table 6. The particle scattering term (b_{sp}) is simply the average nephelometer measurements from the entire study. The particle absorption term (b_{ap}) is derived from the product of the average elemental carbon concentrations and an assumed specific absorption coefficient of 8.0 m^2/g. Similarly, the gas absorption term (b_{ag}) is derived by multiplying the average NO_2 concentrations by a specific gas absorption coefficient of 0.45 Mm^{-1}/ppm taken from the work of Hodkinson (1966) and corrected for non-standard altitude. For day, night and combined periods, the particle scattering term is the dominant contributor to total light extinction, contributing over 65 percent in every period. The average particle absorption and gas absorption terms are approximately equal in all periods, each contributing less than 10 percent to total extinction. The Rayleigh term is included here for comparison and is approximately equal to the gas and particle absorption terms combined.

Table 6. Extinction summary by physical type for day, night and combined sampling periods from the CAMS 5 monitoring site.

Extinction type	Day (Mm^{-1})	Night (Mm^{-1})	Day + Night (Mm^{-1})
b_{sp}[1]	46.0	49.0	47.5
b_{ap}[2]	6.1	5.8	6.0
b_{ag}[3]	5.7	7.2	6.5
b_{sg}[4]	12.8	12.8	12.8

[1]as measured with a heated nephelometer at 530 nm

[2]derived from C_{el} concentrations and an assumed specific absorption coefficient of 8.0 m^2/g

[3]derived from NO_2 concentrations and a specific gas absorption coefficient of 0.45 Mm^{-1}/ppm

[4]the Rayleigh scattering term corrected for altitude

E. Soil Composition

Elemental compositions of the collected soils as determined by re-suspension and XRF analysis are given in Table 7. For the purpose of simplicity, only those elements with concentrations greater than 0.5 mg per gram of soil are shown in the table. Major elements include Al, Si, Ca, and Fe with lower concentrations observed for S, K, Ti, V, Cr and Pb. Results from CAMS 5 and Bonnie View soils typically agree within 20 percent for most of the elements reported. The uncertainty in the measurements as determined from multiple filter depositions and XRF analysis of the same soil sample is on the order of 8 percent for Si and K, the two elements of particular interest in this analysis.
An expression that relates Si concentration to total soil concentration was calculated from the CAMS 5 soil data by the following:

$$FPM_{soil} = [Si] * 6.4 \qquad (4)$$

where FPM_{soil} is the component of the fine particle mass that is attributable to soil sources, [Si] is the silicon concentration as determined by XRF analysis on the filters and 6.4 is the ratio of soil-FPM to Si as determined from the soil analysis experiment. Here, the assumption is made that all silicon present on the filters is derived from crustal sources.

In this study, K is used as a tracer element for the residential wood combustion source, however this value must be corrected for the soil-derived K that may also be present on the filter. Soil-derived K is subtracted from the total K in each sample by using silicon as a soil tracer and the soil-potassium to soil-silicon ratio determined from the soil analysis. The expression describing this soil-K correction can be described as follows:

$$K'_{soil} = K - ([Si] * K_{soil}/Si_{soil}) \qquad (5)$$

Table 7. CAMS 5 and Bonnie View soil elemental composition as determined by soil re-suspension and X-ray fluorescence analysis

ELEMENT	CAMS 5 SOIL			Bonnie View SOIL		
	Average (mg/g)	S Dev (mg/g)	Rel Dev (%)	Average (mg/g)	S Dev (mg/g)	Rel Dev (%)
Al	101.1	8.9	8.8	89.6	19.6	21.9
Si	155.1	12.5	8.1	137.4	24.4	17.7
S	0.9	0.1	13.5	0.7	0.1	9.7
K	10.2	0.9	8.7	8.1	0.5	6.2
Ca	101.0	11.9	11.8	96.6	11.6	12.0
Ti	5.5	0.4	6.9	4.7	0.4	7.7
V	0.6	0.3	48.4	0.5	0.1	22.6
Cr	1.3	0.7	58.6	0.9	0.1	10.1
Mn	5.4	1.9	35.1	4.3	0.2	5.3
Fe	32.7	3.5	10.8	31.2	1.5	4.8
Pb	0.5	0.3	56.3	0.4	0.1	14.9

Notes: Copper, Zinc and Tin are not shown since brass beads were used in the soil re-suspension apparatus

Trace elements, those with concentrations less than 0.5 mg/g are not shown in this table

The relative measurement uncertainty is given by the percent error (Rel Dev) which is the standard deviation (S DEV) expressed as a percentage of the average value

where K'_{soil} is the soil-corrected potassium concentration, K is the total measured potassium concentration, K_{soil} and Si_{soil} are the elemental concentrations of potassium and silicon in soil as experimentally determined, and [Si] is the silicon concentration for the sampling period of interest.

F. Factor Analysis

Factor analysis is a statistical procedure that can be applied to a data set composed of many variables that will allow a simplification of the data set by grouping the variables into subsets or factors. The technique is useful for exploring relationships among variables and, in its application to ambient aerosol that has been analyzed for elemental content, can be a useful predictor of major pollution sources encountered in the region. Factor analysis results were used only in a diagnostic capacity in this study. That is, factor solutions were used to provide supportive evidence for the presence of major source categories expected to be impacting on Dallas air quality and the selection of good tracer elements for these sources. Elements were selected for inclusion in the factor analysis procedure when their average measurement uncertainty (Table 3) was less than 30 percent. A normalization procedure as described by Henry (1977) was used to provide an improved resolution of the various factors in the data set. All elemental concentrations were divided by the corresponding fine particle mass for the same 12-hour sampling period in order to express the element concentrations in terms of mass of element per mass of collected aerosol. This procedure has been shown to be effective in removing the effect of a so-called meteorological factor, which is related to the mixing volume into which the pollutants are emitted. Failure to correct for this meteorological factor can result in a factor analysis solution that tends to group all sources under a single meteorological factor. The analysis results for

the CAMS 5 fine particle data set are shown in Table 8. The best solution for this data set resulted in a 4 factor solution which accounted for 70 percent of the variance in the data set. The first factor shows high loading for crustal species such as Fe, Ca, and Si and is clearly associated with the crustal source. A second factor shows high loadings for Cl, K, Al and Cu and, by virtue of the high K loading, is linked to residential wood combustion sources, since K is a well established tracer for combustion products of cellulosic materials. The high loadings for Al and Cu on this factor are best explained by the presence of a sampling artifact detected on several of the dichotomous samplers.[1]

The factor solution shows a partitioning of K between the soil source and the wood combustion factor with a higher loading on the wood combustion factor. This observation is not surprising since as noted above, soil and wood combustion are both sources of potassium. High loadings for both Pb and Br on the third factor clearly suggest a link with the vehicular source. A fourth factor with high loadings for Se

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1. Detailed inspections of exposed fine and coarse filters from the dichotomous sampler used to collect samples in the evening hours revealed the presence of large (>20 micrometer) particles on selected filters. A further examination of these particles by scanning electron microscopy (SEM) coupled with energy disperive X-ray analysis (EDX) showed that these particles consisted of aluminum and trace amounts of copper. Additional investigations into this sampling artifact showed that the particles were generated by metal to metal contact between the 10 micrometer inlet and the inlet tube of the dichotomous sampling head. Positioning the dichotomous sampler pump boxes on a non-rigid surface adjacent to the aerosol sampling head appears to accentuate this metal contact by transmission of pump motor vibration to the sampling unit. An estimate of the positive bias expected in the mass measurements was obtained by calculating the "excess" Al on the filter based on the known Al to Si ratio for soil material as determined by the soil analysis work. No attempt was made to correct for this artifact Al since the calculated excess Al on the filters for most cases was less than 2 percent of the total mass on the filters.

Table 8. Factor analysis results for the combined day and night fine particle data set from the CAMS 5 monitoring site.

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4
Fe	.95			
Ca	.92			
Si	.87	.34		
Zn	.51		.31	
Cl		.89		
Al		.85		
Cu		.61		
K	.32	.58		
Br			.84	
Pb	.37		.82	
Sn			.34	
Se				.91
S				.48

and S is strongly suggestive of coal combustion processes. No other major industrial sources are evident from these factor analysis results. Some minor sources may be included in the factors described above by virtue of the fact that they share a common tracer with the sources noted above. For example, lead emissions from industrial point sources could be included in the vehicular factor since Pb would be an element common to both source types.

A three factor solution was obtained on an analysis of the Bonnie View fine particle data with an apparent unclear resolution of the crustal, wood combustion and regional power plant sources. For this data set a violation of the generally accepted practice of maintaining a ratio of 4 to 1 or greater between the number of cases and the number of variables included in the analysis may well explain the uncertain solution obtained.

A factor analysis on the coarse particle data set for the CAMS 5 site resulted in a 4 factor solution that accounted for 73.7 percent of the variance encountered in the data set. A crustal factor is apparent with high loadings encountered for Fe, Ca, K, Si and Zn. The three remaining factors are less clearly related to specific source categories. The first factor shows high loading for Br, Pb and S suggesting a combined contribution of vehicular and regional coal-fired power plant sources. A second factor shows a high loading for Se further suggesting the presence of the regional power plant source. The final factor in this group shows high loadings for Sn and intermediate to low loadings for a number of other elements. The relationship of this factor to clearly defined sources in the Dallas area is uncertain; however, local electronics fabrication industries or construction-related soldering processes may be a possible explanation.

G. Fine Mass Apportionment

The results from the factor analysis solution were used in a qualitative sense to help select the best tracer elements for each of the major sources identified. In this work, Si is regarded as an exclusive tracer for crustal sources. Either Pb or Br can be used effectively as a tracer for vehicular emissions. Although Pb is commonly used as a vehicular tracer, the possibility does exist for other industrial sources in the Dallas area which share Pb as a common emission element with the vehicular source. In an effort to prevent this loss of tracer specificity, Br was chosen as the vehicular tracer. Either S or Se are possible candidates as a coal combustion tracer. Although the factor analysis solution for the CAMS 5 data set shows that Se has a higher loading than does S, sulfur was judged to be a more reliable tracer element due to its higher ambient concentration and resultant lower XRF measurement uncertainty. Strictly speaking, particulate sulfur is not a direct tracer for coal combustion emissions since it is a secondary aerosol formed by oxidation of SO_2 that can be emitted by non-coal combustion sources. However, an examination of an emission inventory for SO_2 for the state of Texas as shown in Figure 6 shows that coal combustion by electric power generation facilities accounts for nearly 75% of all SO_2 emitted.

Potassium is used for the wood combustion source and was corrected for minor contributions from soil as shown by the following expression:

$$K_{wood} = K - K'_{soil} \qquad (6)$$

where K_{wood} is the potassium attributable to the wood source, K is the total potassium and K'_{soil} is the soil-derived component as given by equation 5. Correction for the other two tracer elements, namely Pb and S, were not applied since the concentration of these two elements in soil was insignificantly low.

These selected tracers were then used in a multiple linear regression model with the fine particle mass (FPM) as the dependant variable. A stepwise regression model was employed which tests each variable for the

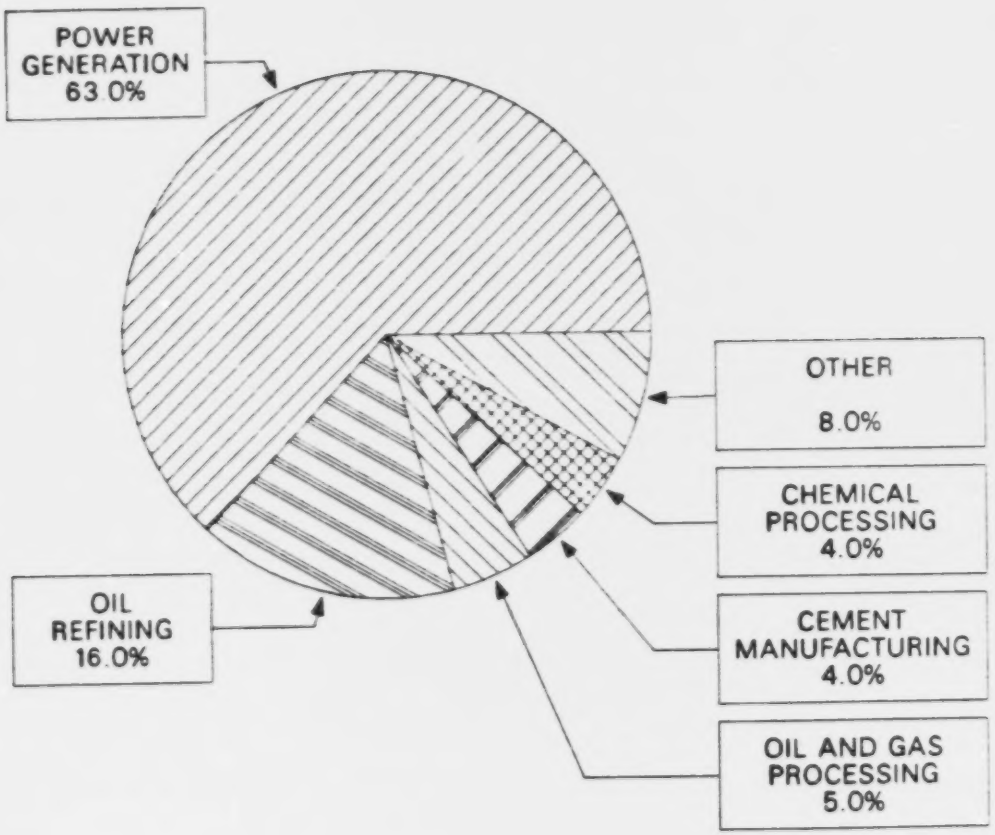

Figure 6. Major sources of SO_2 in Texas as determined by the most recent state-wide emissions inventory.

statistical significance of the hypothesis that its coefficient is equal to zero prior to inclusion in the model. As new variables are added to the model, variable coefficients already in the regression equation are tested again for statistical significance and are dropped if significance criteria are not met. In all regressions reported in this and the following section on visibility apportionment, with the exception of one noted case, a significance level of P=0.05 was set for inclusion of a variable into a regression model and a level of P=0.1 to drop the variable from the equation. A regression analysis with the four tracer elements resulted in a negative coefficient for Si. The regression model was significantly improved by dropping Si as an independent variable and making the appropriate corrections to FPM as shown by the following expression:

$$FPM' = FPM - FPM_{soil} \qquad (7)$$

where FPM' is the fine particle mass concentration after subtraction of the soil-derived FPM. The three-variable regression equation was then:

$$FPM' = A*[Br] + B*[S] + C*[K_{wood}] + constant \qquad (8)$$

and was solved for the day, night and combined CAMS 5 data set. The regression results are given in Table 9, and are favorable as indicated by moderate coefficient standard errors and R^2 values very close to 0.9. The constant terms which are a measure of the un-apportioned fine mass are at an acceptable level of 5 to 10 percent of total measured mass.

By taking the product of the regression coefficient (Table 8) and the average concentration of each tracer element (Table 3) a fine mass apportionment was calculated for the CAMS 5 day and night sampling periods as shown in Table 10. The soil contribution to FPM was calculated using the average Si tracer concentration as shown in equation 4. The coal combustion source dominates all other sources in its average contribution to the total fine particle mass for the day period whereas the wood combustion source dominates during the night periods. The

Table 9. Fine particle mass regression equation results for the CAMS 5 day, night and combined data sets

Period	Coefficient and Standard Error			
	Br	S	K_{wood}	constant (ng/m^3)
Day	580 ± 170	4.1 ± 0.6	64 ± 23	1530 ± 920
Night	380 ± 160	5.7 ± 1.0	86 ± 16	1380 ± 1350
All	400 ± 130	4.6 ± 0.5	90 ± 11	1310 ± 730

Note: Day: 36 cases, R^2 = 0.87
Night: 36 cases, R^2 = 0.89
All: 72 cases, R^2 = 0.88

Table 10. Fine mass apportionment results for the CAMS 5 site day (0700-1900) and night (1900-0700) sampling periods

SOURCE	DAY		NIGHT	
	MASS ($\mu g/m3$)	PERCENT	MASS ($\mu g/m3$)	PERCENT
VEHICULAR	3.1 ± 0.9	24.8 ± 7.4	3.5 ± 1.4	18.1 ± 7.4
COAL COMB.	4.3 ± 0.6	34.5 ± 4.9	5.4 ± 0.9	27.7 ± 4.6
WOOD COMB.	2.8 ± 1.0	22.2 ± 8.1	8.4 ± 1.6	43.5 ± 8.2
SOIL	0.8 ± 0.1	6.3 ± 0.6	0.7 ± 0.1	3.7 ± 0.3
OTHER	1.5 ± 0.9	12.2 ± 7.3	1.4 ± 1.3	7.1 ± 6.9
SUM	12.6 ± 3.5	100.0 ±28.2	19.4 ± 5.4	100.0 ±27.5

dominance of the wood source in night periods is not surprising since the majority of residential wood combustion typically occurs during the evening hours. Vehicular sources show less variation from day to night than the wood source with greater contributions during the day.

Similar results were obtained for fine mass apportionments carried out on the Bonnie View data set with the coal combustion source a major contributor to fine particle mass. Wood burning was a major contributor at this site as well, although the population density at this site is considerably lower than near the CAMS 5 site and one would expect the degree of local wood combustion emissions to be much lower. This observation further suggests that a pollution cloud of relatively uniform composition extends over the greater Dallas area.

H. Visibility Apportionment

Completion of the fine particle mass apportionment allows a progression to a light extinction or visibility apportionment. The technique used here relates the apportioned mass for each source to light scattering or absorption by means of mass specific scattering or absorption terms derived either from the data set or taken from the literature. The relationship between the concentration of a particular species and the resulting contribution to light extinction can be seen by the following example for the light scattering term:

$$b_{sp}\ (Mm^{-1}) = B_{sp}\ (m^2/g) * [mass]\ (\mu g/m^3) \qquad (9)$$

where b_{sp} is measure of light scattering or visibility degradation and is obtained by the product of the specific scattering coefficient, B_{sp} and the mass concentration. A similar expression can be used for the two absorption terms, b_{ap} and b_{ag}. For particle absorption, b_{ap}, elemental carbon concentrations are used in the mass term as this species is responsible for nearly all light absorption. For the gaseous absorption component, b_{ag}, NO_2 concentrations are inserted in the mass term since this gas is the only light absorber at the visible wavelength of interest

in this study. The specific scattering coefficient, B_{sp}, was derived for each source from the data set using the regression re-normalization procedure described by Currie et al (1984). In this procedure the selected tracers are regressed against the measured light scattering values. The resulting coefficients are then divided by the coefficients determined from the regression of the same tracers against mass (Table 9) in order to yield a specific scattering efficiency for each source type. The results from this calculation as carried out for the combined CAMS 5 data are shown in Table 11.

Table 11. Specific scattering coefficients (B_{sp})[1] and standard errors for the CAMS 5 combined data set.

Source	B_{sp} (m^2/g)
Coal combustion	5.2 ± 0.5
Vehicular	1.7 ± 1.3
Wood Combustion	2.4 ± 0.6

[1] from heated nephelometer measurements

As expected, the specific scattering coefficient for the coal combustion source is greater than those values obtained for the other sources and is consistent with values reported by other researchers. White and Roberts (1977) report a value of 5.4 m^2/g for a Los Angeles study, Shah et al (1983) report a value of 4.9 m^2/g for a Portland study and Lewis et al (1986) report a value of 5.6 m^2/g from a recent study in Denver. It is important to note that these values are derived from measurements on "dry" aerosol and are likely to be much lower than those encountered in ambient air. Ammonium sulfate aerosol is deliquescent at a relative humidity in excess of 79% and will exhibit particle growth and refractive index changes in humid air which can greatly enhance the particles' light scattering efficiency. During a recent Denver study, Lewis et al (1986)

report a specific scattering coefficient for sulfate aerosol as derived from unheated (ambient temperature) nephelometer measurements of 10.2 m^2/g, nearly a two-fold increase over the scattering efficiencies reported for a "dry" sulfate aerosol.

The scattering efficiencies for the vehicular and wood combustion sources are lower by about a factor of 2 from the sulfate aerosol and are somewhat lower than values reported by others. The high uncertainty (P=0.2) associated with the specific scattering coefficient for the vehicular source reflects a strong colinearity between the Br and K_{wood} tracer variables when regressed against the nephelometer data. The Si tracer was also included in the regression against the b_{sp} parameter, however it was clearly not significant as a predictor of b_{sp}. Although the error term associated with the specific scattering coefficient for the wood combustion source was larger than anticipated, in light of the reasonable comparison of these statistically derived specific scattering coefficients with those reported in the literature, they were used in the following visibility apportionment steps. No attempt was made to include any coarse particle tracers in these regressions since theoretical evidence indicates that mass specific scattering efficiencies are an order of magnitude lower for coarse particles as compared to fine particles (Lewis, 1981). A regression of fine particle mass against the nephelometer data for the combined data set results in a specific scattering coefficient for all sources combined of 2.8 m^2/g, a value in the range reported for other urban studies.

A similar regression procedure was applied using C_{el} as the dependant variable with poor results. Only the vehicular and regional tracers were picked up as statistically significant by the regression routine. An unsatisfactory R^2 value of 0.58 and a residual term that was nearly 70 percent of the dependent variable were obtained. In light of this poor regression result, an alternate choice was made to use a specific absorption coefficient of 8.0 m^2/g and source emission profiles for the three major source categories in order to estimate their C_{el} contributions. The source parameter of most interest here is the ratio of C_{el} to FPM since the FPM contribution from each source has been determined by the mass apportionment model. For the wood combustion

source C_{el} to FPM ratio, a survey of values reported in the literature shows a range from 0.04 to 0.33 (Watson, 1979; Dasch, 1982). The extent of the range reported is certainly a result of both the type of wood and combustion conditions chosen. For this study, a C_{el} to FPM ratio of 0.07 was chosen based on work completed in a winter visibility study done in Albuquerque (Zak et al, 1984) and results reported by Lewis et al (1986) from a Denver study.

Derivation of a C_{el} to FPM ratio for the vehicular source is somewhat more complex since the vehicular fleet is composed of gasoline-powered and diesel-powered vehicles with very different emission characteristics. An elemental carbon emission estimate was obtained by using a vehicle use summary for Dallas county as compiled by the Texas Air Control Board coupled with FPM emission rates per mile and C_{el} to FPM ratios for each vehicle category as determined by source testing (Muhlbaier, 1982). The results of this source estimate are shown in Table 12. An overall C_{el} to FPM ratio of 0.38 results for the entire vehicular source. According to this estimate, the diesel component of the fleet, although accountable for only 11 percent of the total miles traveled, contributes 53 percent of the total FPM and 95 percent of the elemental carbon. When the vehicular FPM is multiplied by this ratio of 0.38, the amount of C_{el} is overestimated for nearly every period as compared to observed C_{el} concentrations. In light of the uncertainties associated with the vehicle fleet composition and their emission characteristics, an alternative method is used whereby the C_{el} to FPM ratio for the vehicular source is derived directly from the CAMS 5 data set. The daytime C_{el} concentrations were corrected to account for the small wood combustion source contribution and daytime FPM was corrected to subtract out the non-mobile FPM contributions. After these corrections, the C_{el} to FPM ratio for the entire vehicular source, including gasoline and diesel powered vehicles, was calculated for each daytime sample. An average value of 0.26 ± 0.12 was obtained and used for following visibility apportionment calculations.

An estimate of 0.02 for the C_{el} to FPM ratio for a typical coal-fired power plant was obtained from recent work by the EPA in Denver where source samples from coal-fired power plants were collected and characterized for their C_{el} and FPM content (Stevens, 1988).

Table 12. Vehicular fine particle emission characteristic as based on local Dallas vehicle mix and published source signatures

	% VMT[2]	FPM/MILE[3]	% FPM	C_{el}/FPM[4]	%EC
Gas cars (catalyst)	47.8	1.0	8.5	0.12	2.6
Gas cars (pre-catalyst)	12.0	8.0	17.1	0.02	0.9
Lt duty gas trucks (catalyst)	15.6	1.0	2.8	0.12	0.9
Lt duty gas tracks (pre-cat)	8.0	8.0	11.4	0.02	0.6
Heavy duty diesel trucks	6.9	27.5	33.7	0.68	59.9
Heavy duty gas trucks[1]	4.9	8.0	7.0	0.02	0.4
Diesel cars	3.0	27.5	14.7	0.68	26.0
Lt duty diesel trucks	1.0	27.5	4.9	0.68	8.7
Fleet average C_{el}/FPM				0.38	
Diesel contribution to fleet			53.3		94.6

Notes:

[1]All Heavy duty gas trucks are assumed to be pre-catalyst equipped

[2]Percent vehicle miles traveled data (VMT) are from Texas Air Control Board compilations for Dallas county

[3]FPM/MILE data from Muhlbaier (1982) is average of two test driving cycles and is normalized to gas car FPM emissions per mile (Table 4).

[4]C_{el}/FPM data from Muhlbaier (1982), and is average of two test driving cycles (Table 4).

Light absorption by ambient NO_2 was apportioned to the major sources of interest by performing a regression of the selected tracers against NO_2 as the dependent variable. The regression results show the vehicular source as the only significant predictor of NO_2. A residual term which was nearly 50 percent of the average NO_2 was obtained in the regression. Emission inventory data for Dallas and surrounding counties show substantial NO_x contributions from coal-fired power plants and other coal combustion sources. NO_x contributions are also expected from residential home heating with natural gas. In this estimate however, no attempt is made to apportion NO_2 to these stationary sources and they are left in the "other" category.

The estimates for scattering, particle absorption and gaseous absorption as apportioned to the major sources are given in Table 13.

Table 13. Average daytime light extinction apportionment at 530 nm for the CAMS 5 sampling site.

SOURCE	b_{sp} (Mm^{-1})	b_{ap} (Mm^{-1})	b_{ag} (Mm^{-1})	b_{sg} (Mm^{-1})	b_{ext} (Mm^{-1})	Percent
Coal combustion	22 ± 4	1 ± 1	0	0	23 ± 5	33 ± 7
Vehicular	7 ± 6	6 ± 2	3 ± 1	0	16 ± 9	23 ± 13
Wood combustion	6 ± 3	2 ± 1	0	0	8 ± 4	12 ± 6
Other	5 ± 3	0	4 ± 1		9 ± 4	13 ± 6
Rayleigh	0	0	0	13 ± 1	13 ± 1	19 ± 1
Total	40 ± 16	9 ± 4	7 ± 2	13 ± 1	69 ± 23	

The product of the source apportioned fine particle mass (Table 9) with the derived specific scattering coefficient (Table 10) results in an estimate of the average contribution of each source to the light scattering component of the total light extinction. The elemental carbon contributions determined for each source by the use of source apportioned mass and source signatures are multiplied by a B_{ap} value of 8.0 m^2/g to yield an estimate of light absorption for each source. The amount of NO_2

apportioned to each source was multiplied by an altitude corrected specific gas absorption coefficient of 0.45 Mm^{-1}/ppm to arrive at the gas absorption term. The Rayleigh scattering term is also included in this table for comparison. The Rayleigh term is taken from published values in the literature (Ruby and Waggoner, 1981) and is corrected for altitude effects. Of note is the major contribution of the particle scattering term from the coal combustion sources. As noted earlier, these estimates are derived using the scattering properties of "dry" sulfate aerosol, when in fact under conditions of high humidity, the degree of scattering from sulfate aerosol could be significantly greater. This consideration would suggest that the coal combustion source is clearly the greatest contributor to visibility impairment. The vehicular source is second highest in contribution to total extinction followed by the wood combustion source. The "other" category includes the remainder term for the fine mass apportionment and the non-apportioned NO_2.

I. Episodic Fine Mass Apportionment

Two 12-hour periods of high fine mass concentrations were examined in detail in order to derive estimates of source contribution to observed mass and visibility degradation during these worst periods of pollution. The period with the highest mass concentration observed in the study was on Christmas eve, December 24, 1986. Personnel at the CAMS 5 site on this particular evening commented on the odor of woodsmoke being clearly present during the late evening hours. A brief description of the meteorology on December 24 is as follows: The surface synoptic map showed a weak pressure gradient across Texas on the morning of December 24. A weak low was identified over Lubbock while a weak high was centered over Brownsville. Winds into the Dallas area were weak and clearly from the northwest throughout the day. Several days later on December 28, 1986, the highest daytime mass concentrations were recorded.

During the day and evening of December 28, a "white" haze was noted by airport observers and site personnel and was also evident on automatic camera photos during this period. A brief meteorologial description follows: The surface synoptic map showed a weak high pressure area centered over southern Illinois. Winds during the morning hours were generally weak and from the east in the Dallas area. Haze was reported at Love Field at 1 A.M. on the morning of December 28. Winds were reported to be calm for seven consecutive hours from 11 A.M. through 5 P.M. The National Weather service forecast trajectories, valid for this date, showed a very weak surface flow of air into Dallas from east Texas. The 850 mb (5000 ft.) trajectories showed a weak and erratic flow from the south.

Fine mass apportionments were calculated for these two periods using the regression coefficients as derived in Table 9 and the measured tracer concentrations for those particular periods. Table 14 shows the percentage contribution from all sources to the total fine particle mass for the two periods of interest.

Table 14. Fine Mass Apportionment for December 24 (1900-0700) and December 28 (0700-1900), the night and day periods of highest mass concentration

Source	Percent Contribution to FPM	
	December 24 (PM)[1]	December 28 (AM)[2]
Coal combustion	15.7 ± 2.6	59.8 ± 8.4
Vehicular	17.6 ± 7.2	19.5 ± 5.8
Wood combustion	54.8 ± 10.4	15.8 ± 5.7
Soil	1.2 ± 0.1	3.8 ± 0.3
Other	11.8 ± 8.0	1.1 ± 0.8

[1]measured FPM = 60.1 $\mu g/m^3$

[2]measured FPM = 36.7 $\mu g/m^3$

Of particular note is the marked difference in source contributions for the two periods. During the Christmas eve period, the wood combustion source clearly dominates, followed by vehicular and coal combustion sources. On December 28, the coal-combustion source is a major contributor followed by significantly smaller contributions from the vehicular and the wood combustion sources. The wind trajectories noted earlier for this period suggest that long range transport of secondary aerosol from the east may be an important phenomenon during these haze periods. When the fine mass is dominated by secondary aerosol from coal combustion sources, the ratio of scattering to total extinction is very high and the observed pollutant clouds appear white. On the other hand, when vehicular exhaust and wood combustion emissions are important components of fine particle mass, the pollution clouds possess a higher elemental carbon concentration, are more light absorbing, and consequently appear darker in color.

A visibility apportionment was calculated for these two periods using the fine particle mass apportionment and the source signature data described earlier. These results are shown in Table 15 and Figure 7. The distinct difference between these two pollution periods is clearly evident when apportioned light extinction is considered. On the evening of December 24, the coal combustion source contributes on the order of 23 percent as compared to 71 percent on the day of December 28.

J. Visibility Apportionment on Color Selected Data Subsets

An alternate receptor modeling approach using data subsets selected by pollution cloud color, was used in order to test the stability of the results with a different model and underlying assumptions. Since no receptor-based source apportionment model is ideal, exploration of alternate models and assumptions can yield important information on how the selected model's assumptions may affect the results.

Table 15. Visibility apportionment at 530 nm for (a) December 24 (1900-0700) and (b) December 26 (0700-1900), the night and day periods of highest mass concentration

(a) December 24 (1900-0700)

SOURCE	B_{sp} (Mm^{-1})	B_{ap} (Mm^{-1})	B_{ag} (Mm^{-1})	B_{ext} (Mm^{-1})	Percent
Coal combustion	82	3	0	84	23
Vehicular	30	37	10	77	21
Wood combustion	132	31	0	162	44
Soil	0	0	0	0	0
Other	33	0	10	43	12
Total	276	70	20	366	100

(b) December 28 (0700-1900)

SOURCE	B_{sp} (Mm^{-1})	B_{ap} (Mm^{-1})	B_{ag} (Mm^{-1})	B_{ext} (Mm^{-1})	Percent
Coal combustion	311	10	0	321	71
Vehicular	33	41	4	78	17
Wood combustion	38	9	0	47	10
Soil	0	0	0	0	0
Other	3	0	4	7	2
Total	385	59	8	452	100

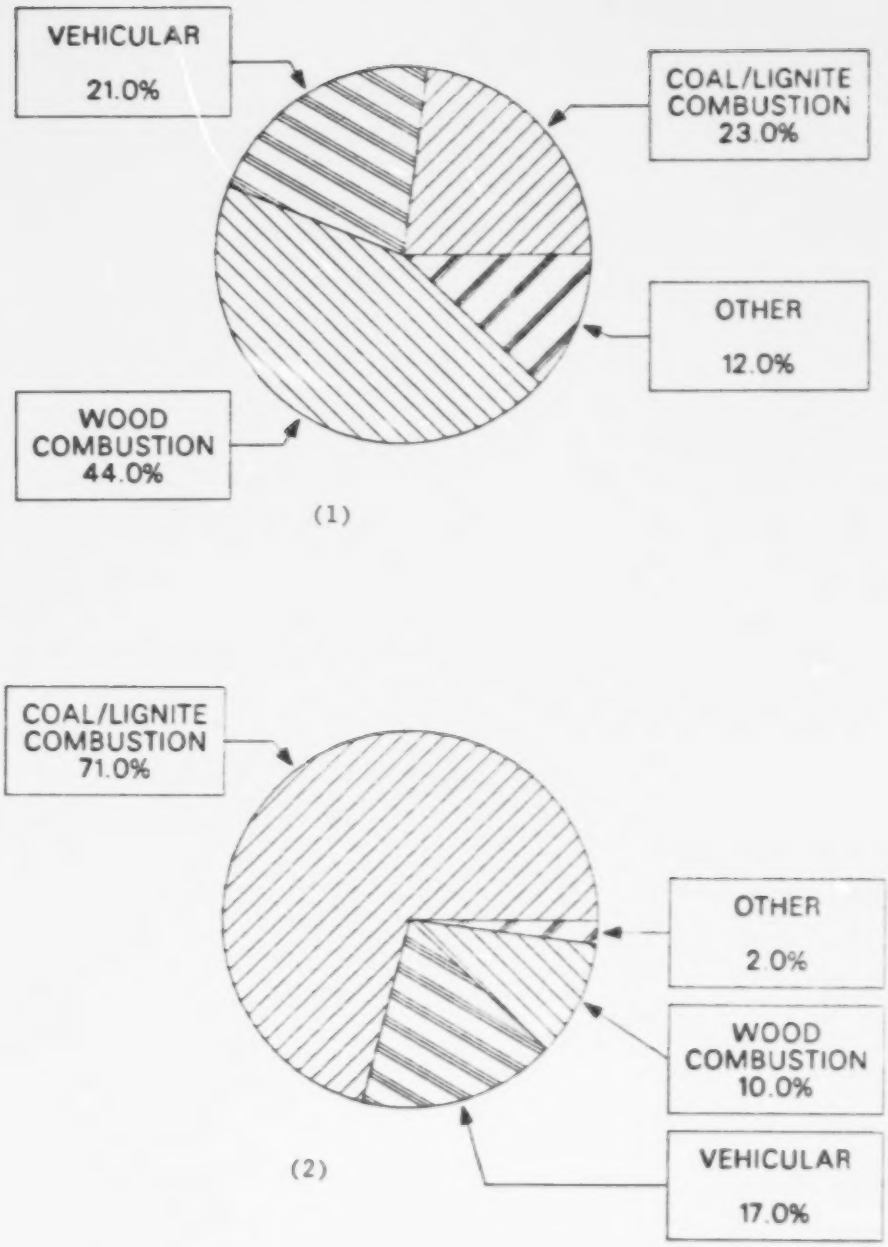

Figure 7. Visibility apportionment at 530 nm for (1) December 24 (1900-0700) and (2) December 28 (0700-1900) the night and day periods of highest mass concentration

In this analysis, a regression of the tracer elements directly against measured parameters of visibility degradation was carried out. Here the assumption is made that measures of all visibility degradation are available from the measurements made at the sampling sites. Nephelometer data, NO_2 gas concentrations, and elemental carbon concentrations are used as parameters directly related to the three major terms contributing to light extinction, namely b_{sp}, b_{ag} and b_{ap}, respectively. Since the Rayleigh term is a constant, it is not of importance here. This approach differs from the model employed earlier, in that source signature data are not required to apportion visibility reduction of the various sources.

A factor analysis was used as a starting point in this model in order to identify the major sources of fine particulate matter in the data set. The factor analysis solutions were similar to those reported earlier with the identification of four major sources including vehicular emissions, wood combustion emissions, coal and lignite combustion emissions and crustal material. Additionally, two minor sources were identified including soldering operations and an unknown source with chlorine to potassium ratios > 0.50. These minor sources were not thoroughly investigated due to the small sample size of the data set. In the few cases where the minor sources had significant mass contributions in a given sampling period, the sampling period was removed from the final data set. These minor sources contribute no more than a few percent to the total observed visibility reduction.

Close examination of the automated photographs of the downtown vista from the south camera site at Cedar Valley College showed that the daytime sampling periods could be partitioned into three distinct pollution categories, namely, clear days, days with a morning brown cloud and days with a persistent white haze. Since the clear day category had only two days with full particulate monitoring data and since these two periods were among the days with lowest pollution concentrations, regression prediction of visibility reduction was not performed for this category. All the remaining daytime periods were partitioned into "Brown" or "White" categories as determined by visual classification of

the photographs by two trained observers who had no knowledge of the pollutant concentrations on those days. To avoid mis-classification errors under occasional fog periods, those time periods when the average relative humidity exceeded 90% were excluded. Descriptive statistics associated with selected parameters are given for these two periods in Table 16. The major differences between the periods included the following: (1) Brown periods had about one third the sulfur concentration of white periods. (2) The absorption to scattering ratio was about 0.40 for brown periods and 0.15 for white periods (3) The brown cloud was layered over the city with a sharp upper boundary whereas the white haze had a non-distinct upper boundary. (4) The brown cloud occurred on cold clear mornings associated with ground based temperature inversions while the white haze was associated with low wind speed conditions. (5) The brown cloud normally dissipated near noon while the white haze often persisted throughout the day.

The visibility reducing contributions from each of the four major source types noted above were estimated with a linear regression model used to determine the relationship between visibility related parameters and selected tracers. All observations were averaged using the same 12-hour period as for particulate sampling. Light scattering by particles was estimated by heated nephelometer data, particulate absorption was estimated by multiplying the elemental carbon concentrations by a specific absorption efficiency of 8.0 m^2/g, and gaseous absorption was estimated by multiplying the NO_2 concentration by a specific gas absorption coefficient of 0.460 Mm^{-1}/ppm, corrected for ambient temperature and pressure. The following elements were chosen as tracers for the four sources: K_{wood} for wood combustion, Br for vehicular emissions, S for coal and lignite combustion and Si for soil. A backward stepwise linear regression procedure was used such that all four tracers were initially included in the model and those that were not statistically significant ($P>.10$) or had negative regression coefficients were removed by a stepwise procedure. The silicon tracer had a negative coefficient for all color selected subsets tested and was removed from the models. The regression results for the brown and white days are

Table 16. Selected fine fraction aerosol, light scattering and absorption averages for white cloud and brown cloud subsets from the combined daytime CAMS 5 and Bonnie View data set.

SPECIES	WHITE CLOUD		BROWN CLOUD	
	average	maximum	average	maximum
MASS ($\mu g/m3$)	16.0	40.3	11.5	24.3
Si (ng/m3)	139	816	154	503
S (ng/m3)	1668	6980	620	1910
K_{wood}(ng/m3)	52	104	45	109
Br (ng/m3)	7	17	5	15
b_{sp} (35°C) (Mm^{-1})	63.0	190.2	34.7	111.0
b_{ap}[1] (Mm^{-1})	4.8	12.0	6.4	12.8
b_{ag}[2] (Mm^{-1})	5.2	17.7	7.5	14.7
α[3]	0.86	0.86	0.71	0.80

[1]derived by multiplying C_{el} concentrations by a specific absorption coefficient of 8.0 m^2/g.

[2]derived by multiplying NO_2 concentrations by a specific absorption coefficient of 0.46 Mm^{-1}/ppm corrected for non-standard temperature and pressure

[3]α is the ratio of b_{sp} to b_{ext} ($b_{sp} + b_{ap} + b_{ag}$) and is a measure of the degree to which light scattering processes dominate in the pollution cloud

reported in Table 17 and the visbility apportionment results are given in Table 18. The wood combustion tracer, K_{wood}, was not a statistically significant variable since it had a high correlation with Br. As a result of this variable co-linearity, the Br term represents both vehicular and wood burning emissions. When K_{wood} was used in lieu of Br as a tracer, somewhat similar results were found, but the goodness of fit (R^2) was much lower. This finding suggests that the vehicular sources had a greater contribution than wood burning during the daytime periods, an observation that is consistent with the earlier fine mass apportionment results.

The estimates of source contributions as determined by the two different receptor models are shown for comparison in Figure 8. Error bars on the graph denote a one standard deviation uncertainty. During white cloud periods, the coal combustion source contributes on the order of 54 percent to total visibility reduction. During brown cloud periods, the vehicular/wood combustion source is the major contributor at 47 percent; however, the coal combustion source is still a significant contributor at 38 percent. Considerable agreement is observed between the two different visibility apportionment models particularly when one considers the uncertainties associated with each model result.

An undesireable feature in both apportionment models used in this study relates to the fact that, strictly speaking, aerosol sulfur is not a unique tracer for coal combustion sources since it is a secondary aerosol formed by oxidation of SO_2 which can also be emitted by other non-coal combustion sources. As has been pointed out earlier however, examination of emission inventories for SO_2 clearly show that coal-combustion is the dominant regional source. The factor analysis solutions show that selenium, an elemental tracer associated with coal combustion processes, correlates reasonably well with sulfur. Possible elemental tracers for other industrial or vehicular combustion processes were tested for their degree of correlation with sulfur. Barium was tested as a tracer of diesel fuel combustion, calcium, as a tracer of cement manufacture and vanadium as a tracer of fuel oil combustion. All

Table 17. Regression results for (a) White Cloud and (b) Brown Cloud subsets of the combined daytime CAMS 5 and Bonnie View data set as classified by automatic camera photos

(a) White Cloud

Parameter	Coefficient and Standard Error			
	Br	S	K_{wood}	constant (Mm^{-1})
b_{sp}[1]	2.63 ± 0.62	0.020 ± 0.002	NS[4]	2.52 ± 5.00
b_{ap}[2]	0.29 ± 0.18	NS	NS	3.07 ± 1.15
b_{ag}[3]	0.57 ± 0.15	NS	NS	1.42 ± 1.19

[1]N=13, R^2=0.97
[2]N=19, R^2=0.16
[3]N=22, R^2=0.37
[4]coefficient not significant (P=0.1)

(b) Brown Cloud

Parameter	Coefficient and Standard Error			
	Br	S	K_{wood}	constant (Mm^{-1})
b_{sp}[1]	3.10 ± 0.92	0.029 ± 0.006	NS[4]	0.14 ± 4.20
b_{ap}[2]	0.56 ± 0.18	NS	NS	3.11 ± 1.12
b_{ag}[3]	0.50 ± 0.20	NS	NS	4.67 ± 1.22

[1]N=16, R^2=0.88
[2]N=19, R^2=0.16
[3]N=19, R^2=0.23
[4]coefficient not significant (P=0.1)

Table 18. Visibility apportionment at 530 nm for (a) White Cloud and (b) Brown Cloud subsets of the daytime CAMS 5 and Bonnie View combined data set.

(a) White Cloud

SOURCE	B_{sp} (Mm^{-1})	B_{ap} (Mm^{-1})	B_{ag} (Mm^{-1})	B_{ext} (Mm^{-1})	Percent
Coal combustion	40	NS[2]	NS	40	54
Vehicular/Wood Comb[1]	21	2	4	27	36
Other	3	3	1	7	9
Total	64	5	5	74	100

[1]As a result of co-linearity between tracers for the vehicular and wood combustion source, these estimates reflect contributions from both vehicular and wood burning sources.

(b) Brown Cloud

SOURCE	B_{sp} (Mm^{-1})	B_{ap} (Mm^{-1})	B_{ag} (Mm^{-1})	B_{ext} (Mm^{-1})	Percent
Coal combustion	18	NS	NS	18	38
Vehicular/Wood Comb[1]	16	3	3	22	47
Other	NS	3	4	7	15
Total	34	6	7	47	100

[1]As a result of co-linearity between tracers for the vehicular and wood combustion source, these estimates reflect contributions from both vehicular and wood burning sources.

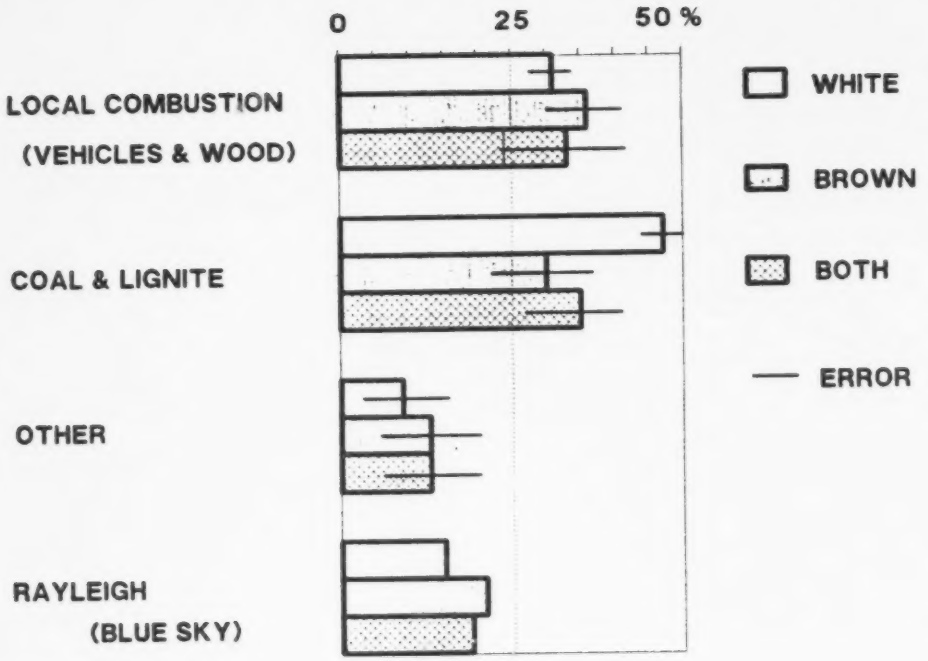

Figure 8. Visibility apportionment at 530 nm for (a) all daytime CAMS 5, (b) all white cloud periods and (c) all brown cloud periods from both CAMS 5 and Bonnieview. Error bars denote a 1 standard deviation error.

tracers tested showed minimal correlation with sulfur. These observations further suggest that cement manufacture, high vanadium fuel oil combustion or barium containing diesel combustion emissions contributed only small or negligible amounts to the measured aerosol Natural gas processing and combustion is another potential source of sulfur with no associated elemental tracers. On the basis of source signature data for this source however, contribution to the observed sulfur is expected to be minor.

On the white days, selenium was an excellent predictor of both sulfur (R^2 =.82) and light scattering as determined by the nephelometer (R^2 =.85). This strongly suggests that coal and lignite combustion were the major source of sulfur and visibility reduction on the white days. The low or negative correlation of aerosol sulfur with NO_x and SO_2 on these days suggests that the sulfur has sufficient time to oxidize to sulfate over a transport path probably in excess of 50 miles. Studies have shown that selenium can be an important tracer of Texas lignites (Texas Department of Health, 1983), (McGinley, 1980). Elemental analysis of lignite sources shows that the selenium concentration varies considerably with the mining locale and even within individual lignite cores.

An examination of the relationship between fine aerosol sulfur and selenium reveals that the selenium to sulfur ratio is quite different on white days as compared to brown days. Based on regression analysis, the selenium to sulfur ratio on white days is 0.0017 ± 0.00017 and .0066 ± 0.00019 on brown days. This observed difference in ratios may indicate the influence of different sulfur sources on the two categories of pollution days. As noted above, the variability in the mass fraction of selenium in the lignite sources may explain these differences. The observed differences could also be explained by statistical error related to, in certain cases, a concentration of selenium deposited on the filters below the detection level of the X-ray fluorescence method (approximately 0.5 ng/m^3). Further analysis is necessary to fully explain the noted differences in the selenium to sulfur ratios. The difference in the selenium to sulfur ratios and an observed correlation

of aerosol sulfur with oxides of nitrogen on brown days suggest that significant portions of the sulfur on the brown days may either originate from non-coal combustion sources or may originate from the coal or lignite sources which have higher NO_x emissions and lower selenium emissions than the aggregate of sources contributing to the white cloud days. On the brown days, some contribution may occur from local sources such as vehicles or natural gas combustion. Local cement plants, which also burn coal, might be contributing, however no correlation is observed between aerosol sulfur and calcium as one would expect since both of these elements are emitted during cement manufacture. Nitrates are another class of secondary aerosols that are derived from vehicular and coal combustion NO_x emissions. The addition of nitrate data in future work may help to better resolve the sources of visibility reduction on brown days.

VI. Conclusions and Recommendations

The principal purpose of this study was to determine the chemical composition of gas and aerosol associated with winter season pollution clouds and to determine relative contributions of the various air pollution sources to visibility impairment in Dallas. These objectives and others were in fact accomplished as a result of this initial investigation into Dallas winter season pollution.

Pollution levels encountered during this three month study were judged to be light to moderate, however no objective visibility measurement data base is available for a definitive comparison. The sampling and analytical techniques employed in this study were of sufficient sensitivity to determine the chemical composition of the aerosol and to identify all major pollution source categories. Apportionments of visibility impairment were constructed for a number of subsets of the total available data set comprising measurements made at both the CAMS 5 and Bonnie View monitoring sites. Major sources making significant contributions to visibility reduction identified in this study include coal combustion, vehicular and residential wood combustion. Although soil derived aerosol was measured at both sampling sites, the crustal source does not make a significant contribution to visibility impairment. On average, coal combustion sources contributed approximately 41 percent to total visibility reduction. The coal combustion source was not further resolved into specific process categories in this study, however available estimates of emission inventories for the Dallas area and surrounding counties strongly suggest that coal-fired electric power generating plants are a major contributor in this source category. The primary visibility reducing species in this coal combustion source category are sulfates. Approximately 30 percent of the visibility impairment was attributable to the vehicular source which comprises both diesel and gasoline powered vehicles. Residential wood burning sources were determined to be of

modest intensity, responsible for an average 14 percent of daytime visibility reduction. Contributions from residential wood burning sources to nighttime visibility impairment was determined to be in excess of 40 percent during selected evening periods. On average, other unresolved sources including residential home heating contributed approximately 14 percent.

Comparison of aerosol composition and visibility apportionment results for separate analysis conducted for the CAMS 5 and Bonnie View sites show no significant differences between these sites despite the fact the one site is in an urban locale and the other is rurally located. This observation indicates that pollution clouds over the Dallas - Fort Worth complex are not locally differentiated but rather are horizontally uniform or mixed over distances in excess of 20 miles. An observed similarity in sulfate concentrations as measured at both sites suggest that local coal combustion sources are not dominant contributors and that, alternatively, long range coal combustion sources play a major role in pollutant contributions in the Dallas-Fort Worth area.

Other observations and conclusions of note were drawn from the data and are summarized below:

Fine particles (less than 2.5 μm aerodynamic diameter) are the major cause of visibility impairment in Dallas. On average, light scattering by these particles is responsible for nearly 80 percent of total light extinction exclusive of Rayleigh scattering. Light absorption by carbon aerosol contributed another 10 percent with gaseous pollutants contributing 11 percent.

The relative scattering efficiency of particles derived from coal combustion sources (primarily ammonium sulfate) was determined to be approximately twice the scattering efficiency of aerosol derived from wood combustion or vehicular sources. The relative

scattering efficiency is probably much greater than 2 since the measurements in this study were made on dry sulfate aerosol when in fact, ambient water vapor associated with these sulfate particles during periods of high humidity can greatly enhance their light scattering efficiencies. Consequently, variations in emissions from coal combustion sources have a more pronounced effect on visibility than these other sources.

The fine particles principally responsible for winter season visibility impairment in Dallas consists largely of organic carbon (42%) and ammonium sulfate (26%) as determined for the day and night combined data set from CAMS 5. Minor species include elemental carbon (5%) and soil-derived elements (4%). Although particulate nitrate species were not measured in this study, they are estimated to be a significant (26%) component of the fine particles.

There is evidence that two dominant pollution scenarios exist in the Dallas region as determined by automatic camera photography carried out during the study. Daytime periods classified into "white cloud" and "brown cloud" categories show that white cloud periods are dominated by sulfate aerosol from coal combustion emissions and that brown cloud periods, while still influenced by sulfate aerosol, have an important contribution from local vehicular and wood combustion sources. Elemental carbon concentrations appear to be an important parameter in determining the apparent "darkness" of the pollution cloud in any given period. Preliminary backward wind trajectory analysis conducted during selected white cloud periods suggest an important sulfate aerosol contribution from coal combustion sources to the east. Conclusions related to the dominance of long range transport are supported by observations of very high sulfate to SO_2 ratios at both sites, a fact that is highly suggestive of "aged" coal combustion emissions derived from distant sources.

Heavy duty diesel trucks and buses contribute disproportionately to visibility impairment as compared to gasoline powered vehicles. Per vehicle mile traveled, such vehicles exhaust on average more than 25 times as much fine particle mass as catalyst equipped vehicles. Furthermore, diesel exhaust contains much more elemental carbon, which is several times more effective per unit mass at scattering and absorbing light than other aerosol species. Using local data for the vehicle fleet composition, calculations show that between 60 and 80 percent of the visibility degradation apportioned to the vehicular source is attributable to diesel powered vehicles while they account for only 11 percent of the total vehicles miles traveled in the area.

A number of recommendations are made for future efforts that would help to further characterize winter season pollution episodes in the Dallas area. Additional data analysis and further experimental work should include the following:

Back trajectory models should be applied to the existing data set in an effort to yield additional information on the sources of the sulfate aerosol measured in the area. Results from trajectory analysis during periods of observed "white" clouds could provide important information on the location of distant coal combustion sources contributing to visibility reduction in the Dallas area. Satellite imagery for these periods of interest may also yield important clues concerning the origins of these aerosols transported from distant sources.

The routine use of a nephelometer should be implemented at the North Dallas site in order to track visibility impairment on a seasonal and yearly basis.

A series of measurements with nephelometers set up to measure both "dry" and "wet" aerosol should be made during the winter and perhaps other seasons. Although the operation of a nephelometer at ambient temperature is more labor intensive, the results would provide important information concerning the increased light scattering properties associated with "wet" sulfate aerosol and thus a more accurate picture of visibility impairment in the Dallas region.

A telephotometer and target system should be employed in future studies that would provide direct measurements of total extinction. These data, when coupled with heated and ambient nephelometer measurements, would provide important information on the scattering efficiency of sulfate aerosol under ambient humidity conditions.

The same visibility apportionment techniques used in this study should be applied to a similar data set collected in the summer season. This would allow one to effectively test the visibility apportionment results in the absence of residential wood combustion sources.

Gaseous and aerosol nitrate species should be measured in future sampling efforts using existing denuder measurement techniques. Information on nitrate species concentrations would provide a more comprehensive visibility apportionment result.

The chemical composition of the emissions from the major sources of pollutants in the Dallas area and upwind of it

should be measured. Consideration should also be given to the analysis of secondary aerosol from these primary sources. These major sources should include the following:

* cement manufacture
* coal combustion
* diesel powered vehicles
* gasoline powered vehicles
* jet aircraft
* lignite combustion
* natural gas combustion
* oil extraction and processing
* combustion of fuel oils derived from Texas crude oils
* wood burning in fireplaces and stoves

These measurements would be used to fingerprint the sources of the emissions and use models such as the Chemical Mass Balance model to also estimate the relative source contributions.

If easterly pollution transport trajectories are found to be important, a monitoring site east of the line of lignite and coal fired power plants in east and south Texas should be established. Such a monitoring location would allow upwind aerosol measurements to help determine if the long range transport of sulfates is coming into Texas from the eastern United States.

References

Alquist, N. C., and R. J. Charlson (1967). "A New Instrument for Evaluating the Visual Quality of Air"; J Air Pollut Control Assoc 17, 457.

Appel, B. R., T. Tokiwa, J. Hsu, E. L. Kothny, E. Hahn and J. J Weslowski, J. J. (1983). "Visibility Reduction as Related to Aerosol Constituents"; California Air and Industrial Hygiene Laboratory Report CA/DOH/AIHL/SP-29, Berkeley, California

Cooper, J. A. and J. G. Watson (1979). "Portland Aerosol Characterization Study (PACS): Final Report Summary"; Oregon Graduate Center, Beaverton, OR.

Groblicki, P. J., G. T. Wolff and R. J. Countess (1981). "Visibility Reducing Species in the Denver 'Brown Cloud' - I. Relationships Between Extinction and Chemical Composition," Atmos Environ 15, 2473.

Currie, L. A., R. W. Gerlach, C. W. Lewis, W. D. Balfour, J. A. Cooper, S. L. Dattner, R. T. De Cesar, G. E. Gordon, S. L. Heisler, P. K. Hopke, J. J. Shah, G. D. Thurston, H. J. Williamson (1984). "Interlaboratory Comparison of Source Apportionment Procedures: Results for Simulated Data Sets"; Atmos Environ 18, 1517.

Dasch, J. M. (1982). "Particulate and Gaseous Emissions from Wood-Burning Fireplaces"; Environ Sci Technol 16, 639.

Dzubay, T. G., R. K. Stevens and C. M. Peterson (1977). "Application of the Dichotomous Sampler to the Characterization of Ambient Aerosols"; X-ray Fluorescence Analysis of Environmental Samples (T. G. Dzubay, ed.), Ann Arbor Seience, Ann Arbor, Michigan.

Dzubay, T. G., R. K. Stevens and C. W. Lewis (1982). "Visibility and Aerosol Composition in Houston, Texas"; Environ Sci Technol 16, 514.

Goulding, F. S., J. M. Jaklevic and B. W. Loo (1978). Development of Air Particulate Monitoring Systems; Lawrence Berkely Laboratory Report No. UCID-8090, Berkely, California.

Henry, R. C. (1977). "The Application of Factor Analysis to Urban Aerosol Source Identification"; in Proceedings of the Fifth Conference on Probability and Statistics, American Meteorological Society, Boston, Massachusets, pp 134-138.

Hodkinson, J. R., (1966). "Calculations of Colour and Visibility in Urban Atmospheres Polluted by Gaseous NO_2"; Air Water Pollut Int J 10, 137.

Horvath, H. (1981). "Atmospheric Visibility"; Atmos Environ 15, 1785.

Johnson, R. L., J. J. Shah, R. A. Cary and J. J. Huntziker (1981). "An Automated Thermal-Optical Method for the Analysis of Carbonaceous Aerosol" in Atmospheric Aerosol: Source/Air Quality Measurements; ACS Symposium Series, No. 167, American Chemcial Society, Washington, DC, 223.

Koschmieder, H. (1924). "Theorie der Horizontalen Sichweite"; Beitr Phys frei Atmos 12, 33, 171.

Lewis, C. W. (1981). "On the Proportionality of Fine Mass Concentration and Extinction Coefficient for Bimodal Size Distributions"; Atmos Environ 15, 2639.

Lewis, C. W., and R. K. Stevens (1985). "Hybrid Receptor Model for Secondary Sulfate From an SO_2 Point Source"; Atmos Environ 19, 917.

Lewis, C. W., R. E. Baumgardner, R. K. Stevens and G. M. Russwurm (1986). "Receptor Modeling Study of Denver Winter Haze"; Environ Sci Technol 20, 1126.

Lin, C. I., M. B. Baker and R. J. Charlson (1973). "Absorption Coefficient of Atmospheric Aerosols: A Method of Measurement"; Appl Opt 12, 1356.

Malm, W. (1979). "Considerations in the Measurement of Visibility"; J Air Pollut Control Assoc 29, 1042.

McGinley, A. N., P. J. Clark, R. A. Zingaro and K. J. Irgolic (1980). "Arsenic and Selenium in Texas Lignite"; Intern J. Environ. Anal. Chem 7, pp 295-314.

Middleton, W. E. K. (1952). Vision through the Atmosphere; University of Toronto Press, Toronto, Canada.

Muhlbaier, J. L. and R. L. Williams (1982). "Fireplaces, Furnaces and Vehicles as Emission Sources of Particulate Carbon"; in Particulate Carbon Atmospheric Life Cycle; (G. T. Wolff and R. L. Klimisch eds.) Plenum Press, New York. pp 185-198.

Ruby, M. G. and A. P. Waggoner (1981). "Intercomparison of Integrating Nephelometer Measurements"; Envir Sci & Tecnol 15, 109-113

Shah, J. J., J. G. Watson, J. A. Cooper, J. J. Huntziker (1983). "Aerosol Chemical Composition and Light Scattering in Portland, Oregon"; Atmos Environ 18, 235.

Stevens, R. K. (1988) personal communication.

Texas Air Control Board (1988). "Texas Air Control Board Laboratory Manual: Determination of Suspended Particulate Matter in the the Atmosphere (High Volume Method), Dichotomous Samplers"; V. Anselmo (ed), Texas Air Control Board, Austin, Texas.

Texas Air Control Board (1988) "Quality Assurance Plan for the Dallas Winter Visibility Study"; document in final preparation; Texas Air Control Board, Austin, Texas.

Texas Department of Health (1983). "A Radiological Study of Lignite and Western Coal-Fired Power Plants in Texas". Texas Department of Health, Austin, Texas, pp20-23.

Watson, J. G. (1979). Ph.D. Thesis, Oregon Graduate Center, Beaverton, Oregon.

Whitby, K. T., and B. Y. H. Liu (1973). Advances in Instrumentation and Techniques for Aerosol Generation and Measurement; Particle Lab Publication No. 216, Mech Engr Dept, University of Minnesota.

White, W. H. and P. T. Roberts (1977). "On the Nature and Origins of Visibility-Reducing Aerosols in the Los Angeles Air Basin"; Atmos Environ 11, 803.

Wolff, G. T., M. A. Ferman, N. A. Kelley, D. P. Stroup and M. S. Ruthkowsky (1983). "The Relationships Between the Chemical Composition of Fine Particles and Visibility in the Detroit Metropolitan Area"; J Air Pollut Control Assoc 32, 1216.

Zak, B. D., W. Einfeld, H. W. Church, G. T. Gay, A. L. Jensen, J. Trijonis and M. D. Ivey (1984). "The Albuquerque Winter Visibility Study Volume I. Overview and Data Analysis"; Sandia National Laboratories Report No. SAND84-0173/1.

Zimmermann, K. A. and L. Wright (1985). "Atmospheric Visibility Trends in Dallas-Fort Worth and El Paso, Texas"; Air Pollution Control Assoc 78th Annual Meeting, Detroit, Michigan.